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BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 64, PP. 1-6 JANUARY 1953

CARIBBEAN RESEARCH PROJECT

BY H. H. HESS AND J. C. MAXWELL

ABSTRACT

This paper is an introduction to the three articles that follow it. It outlines a broad plan of continuing research on the Caribbean region aimed at the problem of origin of island arcs and their development into alpine mountain systems. The present phase of the investigation is concerned largely with the structure and the determination of the exact sequence of events in the history of the eastern portion of the Caribbean so that the geophysical data already in hand may be interpreted. Major results of the last few years are summarized.

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INTRODUCTION

This note sets forth the plan of research on a major geological problem and summarizes progress made and ends to be achieved. We and our colleagues have been actively engaged in this project for a number of years. Three of the detailed studies, by Dengo, Smith, and Christman, which form the building blocks for the overall project, appear in this issue. Other studies already published are given in the list of references. Three more on Venezuela by J. C. MacLachlan, J. R. Bushman, and D. B. MacKenzie are still in progress, and the present authors are preparing summary papers dealing with major problems of the Caribbean area (Fig. 1).

The beginning of this research stems from the work of R. M. Field in the Bahamas during the late 1920's. This led to an invitation to Vening Meinesz to participate in a gravity-measuring cruise of the U.S.S. Submarine S-48 (Hess, 1933) and in the subsequent cruise of the U. S. S. BARRACUDA with Ewing, Hoskinson, and Hess (Hess, 1938). Since the war the investigations have been greatly expanded, facilitated by a contract between the Office of Naval Research and Princeton University (N6onr-27008), and by generous support of the field mapping in Venezuela by the Dirección de Geología (A. Schwarck Anglade, Director) of the Ministerío de Minas e Hidrocarburos of the Republic of Venezuela.

SCOPE AND PLAN OF INVESTIGATION

In the broadest terms, we are investigating the sequence of events and processes involved in the development of an alpine-type mountain system. We are particularly interested in the earlier stages of this development, beginning with the island arc which later evolves into the mountain system. In mountains where a great amount of work has already been done, such as the Alps, the Scottish Highlands, or the Appalachians, these earliest stages are obscure. Later epochs of deformation and metamorphism and vast amounts of igneous intrusion have destroyed much of the record of the early

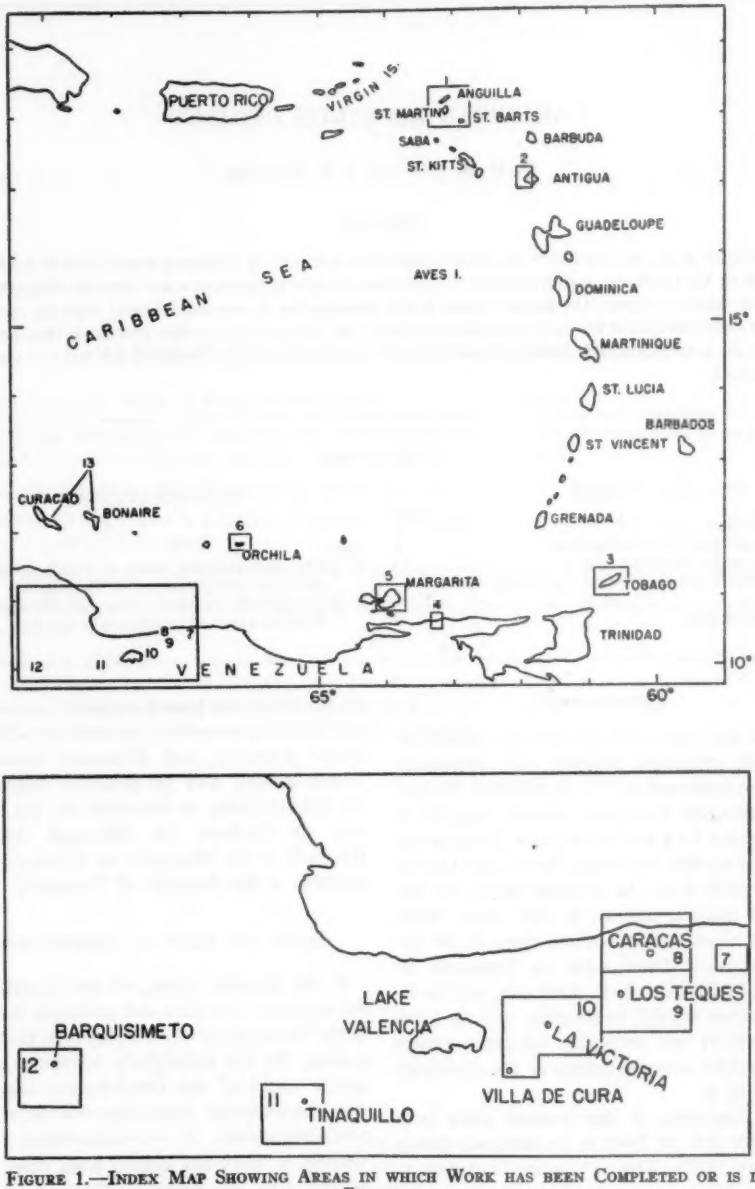

FIGURE 1.—INDEX MAP SHOWING AREAS IN WHICH WORK HAS BEEN COMPLETED OR IS IN PROGRESS

Key

1. Christman (1953)
2. Christman, in preparation
3. Maxwell (1948)
4. Maxwell-Dengo (1951)
5. Hess-Maxwell (1949)
6. Hess, unpublished report
7. Hess-Dengo, unpublished report
8. Dengo (1951; 1953)
9. Smith (1953)
10. MacLachlan, in progress
11. MacKenzie, in progress
12. Bushman, in progress
13. Maxwell, reconnaissance of older rocks, unpublished report

stages, and part has been lost by erosion or hidden by younger sediments.

Since Vening Meinesz's epoch-making discovery of the large negative gravity anomaly belt in the East Indies 25 years ago, there has been no thorough reanalysis of the problem of mountain building. Current literature and texts give Meinesz's results and those of his collaborators, Umbgrove, Kuenen, Hess, etc., interwoven with hypotheses of a preceding generation obviously inconsistent in many respects with Meinesz's results. The model experiments of Kuenen and Griggs also provide a fertile field for reconsideration of the processes involved. But such overall reanalysis must be based on a re-examination of the field evidence with eyes made keener in the search for the critical facts by an awareness of the implication of Meinesz's results.

For this study we have chosen the Caribbean area, an island arc, with attendant large gravity anomalies, volcanism, and earthquakes. In this area we believe we can trace the transition from island arc to alpine mountain system; some portions are far more advanced in their stage of tectonic development than others. Here also a great body of geophysical and geological data are already available.

The Lesser Antilles area on the eastern margin of the Caribbean is in the youthful island-arc stage, while the Greater Antilles to the north and the coastal ranges of Trinidad and Venezuela to the south have advanced to fully developed alpine structures. The Greater Antilles structures apparently have been fragmented by a series of east-west trending strike-slip faults of immense displacement. While such faults also disturb the southern margin of the Caribbean, it is relatively easier here to trace the structures from the southern end of the negative anomaly strip of the island-arc stage through the conveniently placed islands of Tobago, Margarita, and Trinidad into the folded mountains of the Cordillera de la Costa of Venezuela. It is in this area that most of our effort has been concentrated in recent years (Maxwell, 1948; Hess and Maxwell, 1949; Maxwell and Dengo, 1951; Dengo, 1951; Dengo, 1953; Christman, 1953; Smith, 1953).

Recent Major Developments

The interpretation of the strip of strong negative gravity anomalies in island arcs as given by Meinesz, Umbgrove, and Kuenen (1934) and more explicitly by Hess (1938) is no longer tenable in its original form. There appears to be no granitic and little basaltic crust under the oceans to downfold and produce the anomalies. The refraction seismic work of R. Raitt in the Pacific and the work of Ewing, Hamilton, Hersey, Officer, Press, Worzel, and Wuenschel in the Atlantic shows material probably of peridotitic composition at a depth of ±5 km below the sea floor possibly overlain by basalt and a thin veneer of sediments. Study by Ewing and Press of surface waves from earthquakes also indicates a predominantly peridotitic oceanic crust. Under this interpretation material of relatively high density (3.2–3.3) is brought close to the surface, and the density difference between such a crust and the metamorphosed surficial materials at the core of a downbuckle or downbulge would be much greater than before. The source of the anomaly belt on the convex side of island arcs presumably is the embryonic root of the alpine mountain system and is much shallower, smaller, but of greater density contrast (0.6) than given in earlier analyses. That the crust is bulging or buckling downward in the form given in Griggs' or Kuenen's experiments still seems to be valid, so the change from the structural point of view is not great.

Changing the density of crustal materials in island arcs to a much higher value than previously used will rather drastically change the interpretation placed on details of the anomaly field exclusive of the area over the downbulge. The extreme density contrast between light sediments in basins and the underlying crust should produce much larger anomalies than were previously anticipated, hence the disturbing mass may be considerably smaller than originally calculated.

Samples of the oceanic peridotitic crust are probably available for study, as for example the material found by Ewing *et al.* (1947) on a fault scarp on the Mid-Atlantic ridge (Shand, 1949), St. Paul's Rock (Tilley, 1947), and the olivine bombs (xenoliths) found in many ba-

FIGURE 2.—HYPOTHETICAL RECONSTRUCTION OF GREATER ANTILLES AREA BEFORE STRIKE-SLIP FAULTING

Major axis of the tectonic zone indicated by exposed remnants of Cretaceous metamorphic rocks. Under this hypothesis the overturning of folds in Puerto Rico is consistent with the regional relationships. Solid lines indicate original positions before faulting; dashed lines indicate present positions.

saltic volcanoes (Ross and Foster, 1951). Some of the ultramafic rocks found in the island arcs may actually be exposed peridotite substratum, though all those with which the writers are familiar appear to be intrusive.

Another major change in our reasoning with regard to the megatectonics of the Greater Antilles suggests that the isolated, now fragmented, belts of metamorphic rocks were once joined in a single strip before strike-slip faulting of great magnitude displaced them. This reconstructed strip of metamorphic rocks represents the axis of the mid-Cretaceous downbuckle or downbulge. The tectonic axis is not the present negative anomaly strip north of Puerto Rico and Hispaniola as previously believed. While we have been aware of strike-slip faulting almost since the beginning of our investigation (Hess, 1933), we did not realize the magnitude of the displacements. In all our previous analyses the structure of Puerto Rico appeared to be anomalous. Here the folds are overturned to the north-northeast. If the tectonic axis lay to the north, the overturning should have been southward. In our present analysis the tectonic axis lies to the south-southwest, and the Puerto Rican structures are then in a consistent relationship to it (Fig. 2).

Similar strike-slip faulting affects the southern margin of the Caribbean. We have a fairly clear idea of its nature (though not its magnitude) for the eastern part of this area. Inasmuch as little is known of northern Colombia and Central America we are not able to reconstruct the picture as it was previous to the faulting.

Two contributions of regional importance by Christman and Smith are especially worthy of note. Christman was able to estimate the rate of eastward movement of the crust into the tectogene during the Cenozoic Era. Smith showed that the complex series of events leading to the initial production of the Alpine structures took place in a remarkably short time. Two periods of metamorphism, with the deposition of 10,000 feet of eugeosynclinal sediments between them, and the emplacement of a complex series of igneous rocks all occurred during a small fraction of early Late Cretaceous time.

In the reports which follow Dengo's was completed nearly 2 years before Smith's, and thus Dengo's is modified and in minor respects superceded by Smith's. Dengo had the difficult task of subdividing the Caracas Group into lithologically mappable units, and it was upon his foundation that Smith built.

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Princeton University, Princeton, N. J.

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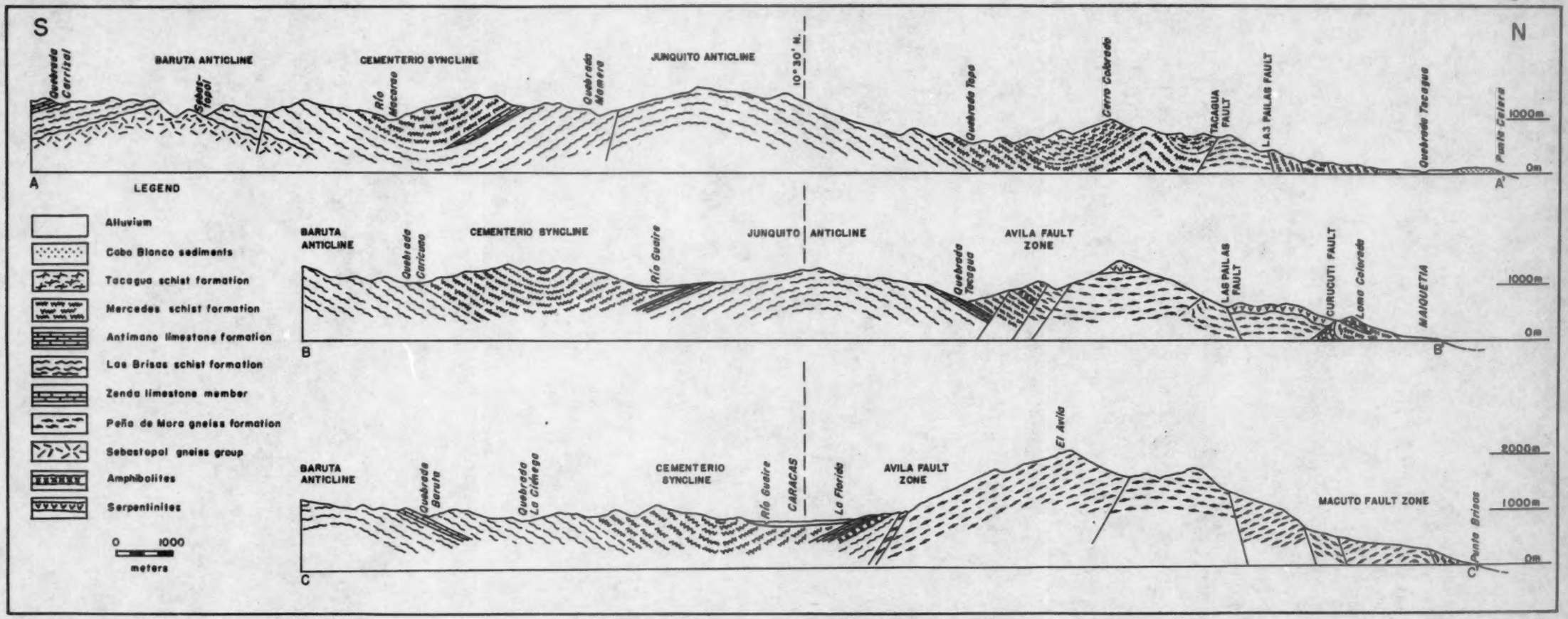

STRUCTURAL CROSS SECTIONS

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BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 64, PP. 7-40 JANUARY 1953

GEOLOGY OF THE CARACAS REGION, VENEZUELA

By Gabriel Dengo

Abstract

The Caracas region is made up of metamorphic rocks which were originally sediments, plus some metamorphosed igneous rocks such as serpentinites and amphibolites. The original sediments, largely if not entirely of Cretaceous age, consisted of sandstones and conglomerates at the base that graded upward into limestones and limey shales. Basaltic rocks were extruded prior to any major deformation, and probably contemporaneously with the deposition of some of the sediments. Some volcanic tuffs were probably deposited in the upper part of the sedimentary succession.

In the Late Cretaceous northern Venezuela was deformed, together with a large portion of the Caribbean region, resulting in the downbuckling of the earth's crust. During this deformation ultramafic rocks were intruded along the axial region of the downbuckle. Continued deformation, probably accompanied by remelting of the crust at depth, rise of the isogeotherms, and migration of solutions into the sedimentary succession, produced the regional metamorphism. The sediments were changed into gneisses, schists, and marbles, and the basaltic rocks into amphibolites.

Further deformation of the region was characterized by thrust faulting followed by normal and transcurrent faulting, and accompanied by folding and regional uplift.

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INTRODUCTION

Scope and Purpose of the Investigation

Along the northern coast of Venezuela two parallel mountain ranges—Cordillera de la Costa and Serranía del Interior—trend east-west. To a large extent they are made up of metamorphic rocks. Their general geological characteristics have long been known, but until now these ranges have not been mapped systematically.

Part of the Cordillera de la Costa is described here (Fig. 1), and an attempt is made to clarify the relationships of the different rock types. Structure and stratigraphy of the metasedimentary formations, and problems of regional importance are emphasized. Several petrological problems are also considered, although a solution is not proposed for all of them. Background information on adjacent regions is included to give a better understanding of the area.

The geological data were plotted on topographic maps, scale 1:25,000, issued by the Dirección Nacional de Cartografía de Venezuela.

The field work was done from June to October 1947, and from July to December 1948. A larger report on the area, including more geographic details and more petrography, has been written in Spanish and published by the Dirección de Geología of Venezuela. The present paper follows the general outline of the Spanish report but is more condensed, and some of the concepts have been modified in the light of field work carried on in near-by areas during the latter part of 1949.

Previous Work

The first mention of the geology of the Caracas region appeared in Humboldt's *Trip to the equinoxial regions of the New Continent* written between 1799 and 1804. Later Karsten (1850–1852) described the region. In 1860 Wall published on the geology of Venezuela and named the metamorphic rocks of the Cordillera de la Costa the "Caribbean series". Sievers (1887) also visited and described the region. Cortese (1901) wrote a short description of the area between Caracas and La Guaira.

More recently several papers have appeared dealing with the geology of the Cordillera de la Costa. Rutten (1931) gave a cross section from La Guaira to El Sombrero and another from Puerto Cabello to La Cumbre, and described some of the rock types. Lamare (1927) also described some rocks from this region. Liddle (1928; 1946) and Schuchert (1935) have compiled much of the existing information on the geology of Venezuela including, of course, the metamorphic rocks of the Cordillera de la Costa. Bucher (1949) has presented an excellent account of the literature, interpreted in the light of his own field observations. His treatment of the problem of correlation of the metamorphics is the most comprehensive thus far attempted.

The best account of the geology of a large portion of the Cordillera de la Costa and Serranía del Interior is by Aguerrevere and Zuloaga (1937). Their concepts on the stratigraphy and structure of the region have been most helpful during this investigation.

Acknowledgments

During the period June 1947 through May 1949 this investigation was financed mainly by the Instituto Nacional de Minería y Geología[1] of Venezuela, and partly by the Department of Geology of Princeton University. During the second year assistance was also obtained from an Office of Naval Research Contract with Princeton University (contract N6onr-27008).

The author is grateful to Dr. A. Schwarck Anglade, Director of the Instituto, and to Dr. V. M. Lopez, former Director, for all the facilities they have given him to carry on the work. To Dr. H. H. Hess and Dr. J. C. Maxwell, of Princeton University, under whose direction this work has been carried on, he is thankful for the advice given both in the field and in the laboratory, and for reading and criticizing the manuscript. He is also thankful to Mr. R. J. Smith who ably assisted during part of the field work.

FIGURE 1.—INDEX MAP OF NORTH-CENTRAL VENEZUELA
Showing location of Caracas region

PHYSICAL GEOGRAPHY

General Statement

The Cordillera de la Costa and Serranía del Interior lie between the Llanos region of central Venezuela and the Caribbean Sea, and extend from Barquisimeto to the Gulf of Barcelona. Farther east the mountain range extends along the Araya and Paria peninsulas in northeastern Venezuela and continues eastward to form the Northern Range of Trinidad. To the west, in the Barquisimeto region, a topographic and structural depression separates this system of mountains from the Venezuelan Andes.

There are differences of opinion as to the position of the geographical boundary between the ranges. A natural division in the topography is marked by Lake Valencia and the Río Tuy Basin (Fig. 1). It is convenient to consider the mountains north of these basins as the Cordillera de la Costa, and those to the south as the Serranía del Interior, since they are geologically different. This is not the current use of the names, however. In the area around Caracas, the ranges south of the Río Guaire valley are often considered part of the Serranía del Interior (Aguerrevere and Zuloaga, 1937).

The Caracas region, described in this paper, is considered as belonging entirely to the Cordillera de la Costa. On the basis of topographic characteristics it may be divided into three portions: the mountain range north of Caracas,

[1] Now called Dirección de Geología, Ministerio de Minas e Hidrocarburos.

the Caracas valley, and the ranges south and west of Caracas.

Sierra del Avila

The name Sierra del Avila is applied to the mountain between Caracas and the Caribbean coast. This mountain rises from sea level to heights of 2640 m. at La Silla and 2765 m. at the Naiguatá Peak. The northern slopes are steep and rugged and are dissected by deep V-shaped valleys of the several streams which drain directly into the Caribbean Sea. Most of these streams are very short because the divide is only 5 to 9 km. from the coast line. The longest streams are the Río Mamo and the Quebrada Tacagua. Quebrada Tacagua actually originates on the southern slopes of the Sierra del Avila, runs to the west along it for some distance, then cuts it through a deep gorge known as Boquerón. It is probably antecedent.

The straight, almost east-west coast line is controlled by faults. Along most of the coast the sea comes directly against the mountains, except where alluvial fans have been deposited. The Miocene-Pliocene sediments and the Recent alluvial deposits at Cabo Blanco were deposited at the mouth of Quebrada Tacagua. This would favor the idea that Tacagua is an antecedent stream which has existed at least since Pliocene time.

The coast line as a whole has characteristics of a coast of emergence, with pronounced cliffs and terraces. At Arrecife, very recent coral reefs are above water level, indicating that uplift is still taking place.

The southern slope of the Sierra del Avila is characterized by scarps of a fault zone which runs mainly east-west. Streams flowing southward into the Caracas valley cut deep V-shaped valleys into the mountains such as those of the Gamboa, Anauco, and Chacaito rivers.

Caracas Valley

The Caracas valley is a narrow, long, and more or less flat-floored topographic depression crossed from west to east by the Río Guaire, a tributary of the Río Tuy. From Antimano, at its western end, to Petare on the east, it is 25 km. long. Its maximum width is 4 km. in a north-south direction. The average height of the valley is 900 meters above sea level.

The Caracas valley owes its existence to the fault zone along the southern slope of the Sierra del Avila. At present all along the foot of the mountain are piedmont alluvial fans, some of which extend across the valley and gradually intermix with the alluvial deposits laid down by the Río Guaire. Originally the Río Guaire must have flowed closer to the fault zone and almost parallel to it, but rapid deposition of piedmont fans has pushed it southward. Similarly the Quebrada Tacagua flowed along the fault zone but in the opposite direction.

At Petare the Río Guaire suddenly turns south, and its flat-floored, alluvium-covered valley changes to a narrow gorge with steep walls cut into bedrock. The bedrock at Petare has acted as a temporary base level which controls the deposition of alluvium in the Caracas valley.

The southern tributaries of the Río Guaire in this region, such as the Río La Vega, Río Valle, and Quebrada Baruta, have acquired grade in relation to the main level of the Caracas valley. The Guaire and its southern tributaries at present are dissecting their own flood plains, and now run about 4 meters lower than the main valley floor. At Antimano and El Valle there is a terrace 8 to 10 m. above the main valley floor.

Ranges South and West of Caracas

The ranges south and west of Caracas trend about N. 60° E., following the general strike of the rocks. They are much lower than the Sierra del Avila and have gentler slopes. They are cut by narrow valleys, most of which parallel the ranges, though some deep valleys also cut across the ranges.

Small subsequent valleys have resulted from the down-dip lateral migration of streams on rocks less resistant than the average. A more resistant rock overlying these forms the capping to small cuestas on the down-dip side of the valley. Examples of these valleys are those containing the towns of Baruta and El Hatillo.

Summary of Physical Geography

In the Caracas region many streams are in a youthful stage. Others have reached maturity as the result of a temporary base level.

TABLE 1.—STRATIGRAPHIC SEQUENCE OF THE CARACAS AREA

Age	Name	Lithologic characteristics
Upper Miocene to Pliocene	Cabo Blanco group	Sandstone and coarse conglomerate
unconformity		
Uncertain, probably Cretaceous	Caracas group: Tacagua formation	Metavolcanics: sericite-epidote schist
	Las Mercedes formation	Calcareous quartz-mica schist and thin-bedded dark limestone layers
	Antimano formation	Marble and thick-bedded crystalline limestone
	Las Brisas formation	Quartz-mica schist, microcline porphyroblast gneiss, limestone lenses, and conglomerate
unconformity	Peña de Mora formation	Gneiss, in part migmatitic. Corresponds to Las Brisas and probably in part to Sebastopol.
pre-Cretaceous	Sebastopol group	Feldspathic gneiss, in part granitic.

Summary of Physical Geography

In the Caracas region many streams are in a youthful stage. Others have reached maturity as the result of a temporary base level.

The region as a whole is in a stage of maturity, with the trunk streams nearly at grade and their valleys adjusted to the structure of the terrain. The Sierra del Avila is still in a somewhat younger stage.

Along the coast line and in the valleys terraces indicate several periods of uplift, and there is evidence that even now this land is being uplifted.

STRATIGRAPHIC SEQUENCE

General Statement

The stratigraphic sequence (Table 1) south of the Caracas valley was worked out by Aguerrevere and Zuloaga (1937; 1938). North of this valley they named only the Peña de Mora gneiss. In naming the formations they used binomial designations consisting of a geographic and petrographic name, as is the common practice with sedimentary rocks. On the whole the author agrees that their nomenclature is useful, but in some cases the formation names should be extended to include closely related rocks, or new geographic names should be chosen for some unnamed units. The rock units or formations are described, and a comparison is made between the names used here and the existing ones (Table 4).

Description of Formations

Sebastopol group.—Aguerrevere and Zuloaga (1938, p. 259–260) named a gneiss of questionable granitic origin the Sebastopol basal complex. At the type locality in Sebastopol, 23 km. from Caracas, on the road to Los Teques, the gneiss is fine-grained with well-developed foliation consisting of alternating bands of dark and light minerals. The rock is very uniform and is made up of quartz, orthoclase, microcline, plagioclase, muscovite, and biotite. Toward the northern boundary of the outcrop it is medium-grained and has a gneissic granite structure. It here most resembles a deformed igneous rock.

Chloritic bands within the gneiss cut across

its foliation at angles between 5° and 10°. These are thin, and they swell and pinch and form anastomosing systems. They are interpreted as having been originally basic igneous dikes which are now deformed and chloritized. They do not penetrate the rocks above the gneiss.

Small cross-cutting quartz veins are present in the gneiss, but they are much less common than in the overlying schists.

Although the gneiss at Sebastopol is lithologically fairly uniform, it must be variable in composition because, in the overlying rocks, there are pebbles of undeformed granite and of granite pegmatite. These pebbles apparently were deformed much less severely than the underlying gneiss because they were embedded in rather plastic sedimentary material and later in weak mica schists during the regional metamorphism.

The writer concurs with Aguerrevere and Zuloaga that the Sebastopol gneiss is the basement over which the rocks of their Caracas group were laid down. The unconformity between the Sebastopol gneiss and the overlying rocks can be seen at the southern boundary of the main outcrop, in a small creek near kilometer 24 of the Caracas–Los Teques highway. Although it is poorly exposed, there is a sudden change from gneiss to a quartz-mica schist with conglomeratic layers containing pebbles of granite and quartz. The linear structure also differs; it is of the pencil type in the gneiss, while the overlying schist has lineation developed as microcorrugations of the micaeceous layers.

TABLE 2.—CHEMICAL ANALYSIS AND NORM OF SEBASTOPOL GNEISS

SiO_2.....	75.70%	Q	38.91	
Al_2O_3.....	13.02	C	1.68	
Fe_2O_3.....	.76	Or	21.68	
FeO.....	.74	Pc Ab (85)	28.82	33.96
		Pc An	5.14	
MgO.....	.33	Hy En (63)	.80	1.26
CaO.....	1.11	Hy Fs	.46	
Na_2O.....	3.47	Mt	1.16	
K_2O.....	3.69	Il	.30	
H_2O+....	.56	Ap	.17	
H_2O-....	.06			
TiO_2.....	.16	Sp. G. at 21°C 2.65+		
P_2O_5.....	.05	Analyst: E. Chadbourn		
MnO.....	.04			
Total...	99.69			

A sample of the Sebastopol gneiss from the type locality observed under the microscope is a fine-grained rock, with crystals ranging from 0.5 to 2 mm. It consists of orthoclase, microcline, plagiocase (albite-oligoclase), quartz, and muscovite as the main constituents, with accessories of biotite, epidote, magnetite, and apatite. Orthoclase and microcline are the most abundant feldspars, while the plagioclase occurs in lesser amounts. The plagioclase and orthoclase show cataclastic structures, such as fracturing of the crystals and bending of the twin lamellae, and are partly altered. On the other hand, microcline appears fresh, undistorted, and contains inclusions of quartz, indicating a crystalloblastic origin. Quartz occurs in small grains, many of which are the result of crushing. Muscovite, biotite, and epidote are associated in thin bands alternating with thicker bands of feldspars and quartz. The chemical analysis and the norm of this rock are given in Table 2.

A sample from an outcrop near Los Lechozos (5 km. south of El Valle) is similar to the one described above. It shows cataclastic structure. It contains no microcline, biotite, or epidote. The orthoclase is probably recrystallized because there are some quite fresh and undeformed grains.

Most of the field data and the microscopic observations point toward a granitic origin for much of the Sebastopol gneiss. However, the rock has been so much deformed, mainly mechanically, that most of the original texture has been destroyed. Furthermore, the gneiss may include rocks of varying origins.

Since in this work the gneiss in question was not studied in detail, the name Sebastopol group is provisional until more information becomes available.

Las Brisas formation.—Unconformably above the Sebastopol gneiss rest a thick succession of quartz-muscovite schists with interlayered beds of conglomerate, microcline porphyroblastic gneiss, and crystalline limestones. It has been considered as one map unit, although locally the microcline gneiss and the limestones are mapped as separate units to bring out structural features. Metamorphic facies changes within the quartz-mica schists may be useful for mapping smaller units, if more detail is desired. Among them the presence of garnet toward the northern part of the area is the most evident in the field.

The main part of the formation consists of

quartz-mica schist. It is well exposed at Las Brisas, about 4 km. south of El Valle, and also in road cuts along the Caracas–Los Teques highway. In these exposures conglomeratic layers with pebbles of quartz and granite occur in the lower part of the schist. The conglomeratic layers are, however, a minor part of the rock which is principally a fine- to medium-grained quartz-muscovite schist. It is coarser-grained near the base of the formation where it has much detrital quartz.

In the northern part of the area, for instance in the exposures along the highway from Caracas to El Junquito, the quartz-mica schist becomes coarser-grained and in several places has sandy beds which still show the original bedding of the rock. In this area also conspicuous graphitic layers occur toward the top of the formation. Upstream along the Quebrada Tacagua Arriba, which cuts the schist normal to the strike, several lithologic changes occur. Garnet becomes very conspicuous, particularly along certain layers, and the schist in part becomes gneissic, having orthoclase as an important constituent. At the lower part of the section there exposed, thin aplites within the schist parallel the foliation, and quartz veins are more abundant. These quartz veins are mainly parallel to the foliation of the schist but a few cut the foliation. These characteristics prevail north of a line which runs from about 2 km. north of El Junquito to the north of Catia. In other words, the garnet isograd approximates this line.

A typical sample of the garnetiferous rock consists of about 40% quartz and 40% muscovite. Next in abundance are garnet, chlorite, and sphene, with minor amounts of apatite, an altered amphibole, probably actinolitic hornblende, and graphite. The schistose structure results from the nearly parallel arrangement of muscovite flakes and the alternation of bands of different minerals. Quartz is completely recrystallized, showing sinuous borders. Garnets are the largest grains, reaching 2 mm. in diameter. They are diablastic, with inclusions of quartz, and several grains show helicitic structure where the quartz inclusions are arranged in spirals. The chlorite is an alternation of garnet and amphibole and may be the result of retrogressive changes in the rock.

Interlayered with the quartz-mica schist, particularly in the southern part of the area, is a microcline-quartz-muscovite gneiss. This rock is very resistant to weathering and usually forms small ridges. It is best developed around the Baruta Valley, where it is coarse-grained and forms thick beds, becoming finer-grained and thinner toward the east and west. Microcline, which occurs mainly as porphyroblasts, is probably the result of some special characteristic in the original sedimentary rock.

A sample of the microcline-quartz-muscovite gneiss collected near Las Brisas consists of a fine aggregate of quartz, muscovite, calcite, plagioclase, apatite, and pyrite with porphyroblasts of microcline. The quartz occurs in three ways: as very fine grains resulting from cataclasis, larger grains with rounded borders which are probably detrital, and recrystallized grains with sinuous interlocking borders. Small flakes of muscovite are associated with the fine-grained quartz. Microcline is found in irregular crystals ranging from 1.5 to 3.5 mm., which have inclusions of muscovite, plagioclase, and quartz. The microcline is interpreted as having grown within the rock as the result of metamorphism —that is, the crystals are porphyroblasts. This interpretation is based on the facts that the microcline grains are much larger than grains of detrital quartz, that they do not show cataclastic effects as do other minerals in the rock, and that the muscovite and graphite are bent around the borders of the microcline crystals. Black porphyroblasts, as they appear in hand specimen, are the result of graphite which occurs around their margins, apparently pushed outward from matrix as the porphyroblasts grew.

Lenses and irregular masses of limestone are interbedded in the upper half of the quartz-mica schist. The limestone outcrops at Zenda (kilometer 25 on the highway Caracas–Los Teques), at La Mariposa, near Baruta, at La Guairita, and at several places along the railroad to Santa Lucia.

At Zenda the limestone is interlayered with dark-gray, medium-grained microcline gneiss. At La Mariposa pebbles of quartz and granite occur within the limestone. In these two localities layers of limestone alternate with layers of microcline gneiss and schist. The prevailing type of limestone near Baruta and south of Petare is a medium-grained, gray, completely recrystallized rock. A black fine-grained type also occurs. Except for the black type, most of these limestones are massive.

Under the microscope, a sample of limestone collected at the quarry at La Mariposa consists of about 60% calcite, with quartz, microcline, plagioclase (albite-oligoclase), muscovite, graphite, and pyrite. The microcline is porphyroblastic, exactly as in the microcline gneiss which occurs near by. Calcite is completely recrystallized.

The facts that these limestones are isolated masses of irregular shape and dimension, that they are inbedded in a quartz-mica schist which was originally an arenaceous and conglomeratic sediment, and that some of them show questionable algal structures strongly suggest that they were originally biohermal reefs.

The upper contact of the quartz-mica schist formation is difficult to ascertain because it is gradational into calcareous schists and phyllites with quartz and muscovite. The gradation may be observed along the highways from Caracas to Baruta and to El Valle. López (1942, p. 7) has described a similar gradation in the Valencia area. Locally the contact can be fixed more precisely because a distinctive limestone unit separates the quartz-mica schist from the overlying calcareous schist. This condition exists north of the town of Antimano.

Aguerrevere and Zuloaga (1938, p. 259) named the rocks directly overlying the Sebastopol gneiss the Las Brisas formation, which they described as largely conglomerate. They included as part of this formation the Zenda "phase", described as a calcareous, massive, and slightly conglomeratic feldspathic rock which forms the top of Las Brisas formation. The name Zenda is here restricted to the limestone unit within the quartz-mica schist and is considered a member of Las Brisas formation. According to the writer's observations the rocks between the Sebastopol gneiss and the Zenda limestone member consist mainly of quartz-mica schist in which a minor part is conglomeratic. The difference of opinion arises from the fact that Aguerrevere and Zuloaga considered the feldspars within the microcline gneiss and the Zenda limestone as detrital material, while the writer considers them porphyroblastic. It is proposed here to include in Las Brisas formation also the portion of quartz-mica schist above the Zenda member and below either the calcareous schist or the crystalline limestones such as those north of Antimano. The minimum estimated thickness of the entire formation is 800 m., although in places it exceeds 1000 m. The Zenda member ranges up to 75 m.

Peña de Mora formation.—The Peña de Mora formation as mapped includes several rock types. No attempt was made to subdivide it because of the inaccessibility of its area of occurrence and also because it is largely covered by forest or by a deep soil mantle. It is described after the quartz-mica schist because there are strong evidences that the rocks correlate stratigraphically, as has already been pointed out by Aguerrevere and Zuloaga (1938, p. 259) and by the writer (1947, p. 135). This formation was named the Peña de Mora augen gneiss (Aguerrevere and Zuloaga, 1937, p. 8) because of the excellent exposures at that locality. The name is used here in a wider sense and is not restricted to the gneiss with augen structure.

The Sierra del Avila is made up largely of the Peña de Mora gneiss. The best exposures are at Boquerón, where the Quebrada Tacagua cuts a deep gorge across the mountain. Here the gneiss has typical augen structure, is coarse-grained, and consists of dark layers of biotite alternating with light bands of feldspars and quartz. The augen are mostly feldspars. Some dark bands without augen structure have abundant biotite and epidote. The lower part of the formation is predominantly augen gneiss, but toward the top it becomes evenly banded and has distinctive light layers of quartzite. Aplite veins, usually not over 30 cm. thick, cut the foliation of the gneiss at angles between 5° and 10° and branch off into smaller veinlets which inject the gneiss in *lit-par-lit* fashion. Where aplites are abundant the augen structure is more pronounced.

In its upper part the gneiss is garnetiferous and grades into garnet-muscovite schist.

On a ridge 1 km. east of Peña de Mora, there are marble lenses within the upper part of the gneiss. The marble consists of recrystallized calcite, with tremolite and diopside, and has thin layers of tremolite. The maximum thickness observed is 3 m.

Along the southern slopes of the Sierra del Avila the gneiss is mainly of the banded type, with little augen gneiss exposed. A fault zone follows the southern slope of the mountain, and the gneiss has been largely changed to mylonite.

Quartz veins are abundant in the gneiss, both crosscutting and paralleling its foliation, with the latter type more common.

Structurally the gneiss is a competent rock.

In the Peña de Mora area the foliation of the gneiss is horizontal or nearly so and undulates without any complex folding. Even the aplites and quartz veins are nearly horizontal. No true ptygmatic folding has been observed, but a few tortuous veins occur.

The Peña de Mora gneiss cannot be traced into other rocks because it is interrupted on the north and south by fault zones. There are indications, however, that it correlates wholly or in part with Las Brisas formation. The gneiss has marble lenses in its upper part which may correspond to the Zenda member of Las Brisas formation. In the Sanchorquiz area, the gneiss is overlain by calcareous schist and limestone, as is the quartz-mica schist in other localities. Furthermore, the upper schistose garnetiferous unit of the gneiss is petrographically very similar to the garnetiferous metamorphic facies of the quartz-mica schist. In other words, the garnet-muscovite schist is a transitional facies between quartz-mica schist and the augen gneiss. The augen gneiss is probably a portion of the quartz-mica schist modified by introduction of aplitic materials. Or perhaps the augen gneiss and the aplite injections are parallel phenomena which have developed under similar conditions of high-grade metamorphism.

There is a question as to whether the augen gneiss also includes part of the Sebastopol gneiss. This problem cannot be solved with the information now available.

A sample of augen gneiss from Peña de Mora consists of feldspars (orthoclase, microcline, and albite), biotite, muscovite, with quartz, epidote, clinozoisite, apatite, and sphene. The augen consist of aggregates of orthoclase or microcline and quartz. The orthoclase forms small porphyroblasts up to 1 mm. in length. The augen are surrounded by bands of biotite, muscovite, epidote, and clinozoisite. The feldspars, of which orthoclase is the most abundant, make up about 50% of the rock, quartz about 25%, and biotite about 20%. The chemical analysis and norm of this rock are given in Table 3.

An aplite vein within rock described above is made up of a fine-grained aggregate of about 60% orthoclase, 30% quartz, with microcline, biotite, epidote, and apatite. Very possibly much of the feldspar in the augen gneiss is the result of the injection of the aplites.

A sample of one of the dark bands alternating with the augen gneiss was collected at Boquerón. It is fine-grained and consists of about 50% quartz plus orthoclase, and 50% muscovite, biotite, epidote, pyrite, sphene, and apatite. Biotite is the most abundant dark mineral. The rock is completely recrystallized.

A specimen collected in a quarry at El Caribe is also augen gneiss. It is made up of bands of muscovite, chlorite, biotite, and epidote alternating with aggregates of orthoclase, microcline, and albite.

TABLE 3.—CHEMICAL ANALYSIS AND NORM OF PEÑA DE MORA GNEISS

SiO_2	69.70%	Q	30.81	
Al_2O_3	12.88	C	.51	
Fe_2O_3	1.91	Or	28.36	
FeO	3.60	Pc Ab (70)	20.44	29.06
		Pc An	8.62	
MgO	.59	Hy En (27)	1.50	5.50
CaO	1.96	Hy Fs	4.00	
Na_2O	2.42	Mt	2.78	
K_2O	4.79	Il	1.22	
H_2O-	.73	Ap	.34	
H_2O	.06			
TiO_2	.63	Sp. G. at 24°C 2.69		
P_2O_5	.16	Analyst: E. Chadbourn		
MnO	.06			
Total	99.49			

Sphene, apatite, and pyrite occur in minor amounts. Some layers consist almost exclusively of quartz, which is fine-grained and shows sutured borders characteristic of recrystallization. Most minerals are less than 0.5 mm. in diameter, except for small orthoclase porphyroblasts which are over 1 mm.

Several other samples of gneiss from the Río Cojo, Quebrada Chacaíto, and from Topo Palmar de Azucar, about 2 km. northwest of La Silla Peak have much the same minerals, although the proportions vary somewhat.

A sample from the Picacho de Galipán, which corresponds to the upper part of the gneiss formation, consists of about 45% orthoclase, 20% quartz, 15% biotite and chlorite, 10% epidote and clinozoisite, with minor amounts of muscovite, garnet, sphene, apatite, carbonate, and pyrite. Orthoclase forms large crystals, up to 3 mm. in length, usually surrounded by biotite and muscovite. Epidote and clinozoisite are idioblastic, and crystals as large as 1.5 mm. along the *b* axis are found. Biotite and garnet are partly replaced by chlorite.

Antimano formation.—From Mamera to Bella Vista there are several limestone quarries of which the largest are those north of Antimano. The limestone exposed in these quarries presents characteristics different from the Zenda type of limestone, although both are recrystallized. It is believed that this limestone is stratigraphically higher than the Zenda, occurring above the quartz-mica schist and at the base of the calcareous schist. However, the limestone is lenticular and is not found every-

where along the contact. In many places quartz-mica schists grade into calcareous schists without any intervening limestone.

Megascopically it is a crystalline limestone or marble, massive, medium-grained, and light gray. Pyrite crystals are quite common. Its structure indicates complete recrystallization. It does not form a single bed as indicated on the map, but several thick layers alternating with thin quartz-mica schist and greenstone layers. North of Antimano, where it attains its maximum thickness, the limestone is 40 to 50 m. thick. It thins along the strike toward both the east and west. To the east, it is covered by alluvium in the Caracas valley, but crops out again north of La Florida, where it terminates against a fault plane. To the west, it pinches out somewhere between the valleys of Quebrada Mamera and Río Macarao.

There are several other occurrences of this limestone in the Caracas area. Along the north side of the Tacagua valley the limestone outcrops in several places and seems to be more coarsely crystalline than it is near Antimano. Here it is also interlayered with thin mica schist and greenstones. Along the strike, toward the east, it becomes lenticular, and several small bodies are found north of Catia. Crystalline limestone exposed in the Río Mamo is underlain by garnet-quartz-mica schist and overlain by calcareous schist. North of Curucutí is another limestone outcrop which, on the basis of lithology and stratigraphic position, has been interpreted as belonging to the type under discussion.

The writer (1947, p. 137) has expressed the opinion that this limestone is probably equivalent to the Zenda. With the information now available, however, he considers it a different unit occurring stratigraphically above the Zenda. According to this interpretation, no geographical name has been given to it. It is proposed here that it be called the Antimano crystalline limestone, and be considered as a formation. The type locality is .5 km. north of Antimano.

Structurally the Antimano formation is a more competent rock than the overlying and underlying schists. It is incompetent in relation to the greenstones, and was probably incompetent at the time of metamorphism while undergoing recrystallization, because some flow folds have been observed. The limestone has also flowed around lenticular bodies of greenstone with resultant formation of *boudinage* structure.

Representative samples of the Antimano limestone collected in an outcrop north of Catia consist of about 95% calcite, with minor amounts of quartz, muscovite, pyrite, and graphite. The calcite is recrystallized, very commonly twinned, and the average size of the crystals ranges from 0.25 to 0.5 mm. Much of the quartz is detrital.

Another sample, collected in a small quarry on the north side of the Tacagua valley, consists of 85% recrystallized calcite; the remaining 15% is quartz, muscovite, chlorite, orthoclase, tremolite, and pyrite. Most of the calcite is twinned. The quartz is recrystallized. This rock was probably subjected to higher-temperature conditions than the specimen described above, as indicated by the presence of tremolite.

Las Mercedes formation.—It has been stated that conformable calcareous schists overlie the limestones near Antimano, on the Tacagua valley, and on the Río Mamo valley. In other places the calcareous schists are conformable over quartz-mica schist, with a gradational contact.

The calcareous schist consists of about 25 to 50 per cent recrystallized calcite, with much quartz, muscovite, chlorite, and graphite. Pyrite is also relatively common. The rock when fresh is pinkish gray, fine-grained, and usually has very well-developed foliation. It weathers to a dark-red soil, which is covered by denser vegetation than is the quartz-mica schist. It is well exposed on the low hills south of Caracas, as for example at El Portachuelo, between Caracas and El Valle.

A complete section of this formation is exposed along the valley of Quebrada Tacagua. At the lower part of the schist there are thin layers of black, fine-grained limestone, which become less conspicuous in its upper portion. The whole calcareous schist formation is graphitic. Graphite is more abundant toward the top of the formation, giving the rock a characteristically dark color. The schist exposed along the coast is very graphitic.

The calcareous schist contains abundant conspicuous quartz veins. Most of these are short, lens-shaped, and parallel to the foliation planes. They do not interconnect. Very few quartz veins cut the foliation. They seem to be more abundant in the upper part of the formation

and in the outcrops of the northern part of the area mapped. Veins of calcite and ankerite are also common.

Structurally the calcareous schist behaves as an incompetent rock. Everywhere it is very complexly folded and faulted. It has been more tightly folded in the crestal parts of anticlines and in the troughs of synclines. The author has not attempted to map the small folds in this formation; only the major structures are mapped.

In the nomenclature proposed by Aguerrevere and Zuloaga (1938, p. 258), the calcareous schist has been named Las Mercedes formation. The type locality is at the Hacienda Las Mercedes, 3 km. east of Caracas, on the road to El Hatillo. The lower part of the formation, characterized by thin layers of dark-gray limestone, was named Los Colorados member. In the present study no attempt has been made to map the lower member of the formation separately. The minimum thickness estimated for the entire Mercedes formation is about 500 m.

The petrography of the calcareous schist is rather simple. A sample collected at the base of the formation in Quebrada Tacagua is about 50% recrystallized calcite, over 30% muscovite, and the remainder is quartz, chlorite, graphite, sphene, and pyrite. It has a very good foliation due to oriented muscovite flakes and lenticular aggregates of quartz. Graphite is interstitial but also occurs as inclusions in calcite.

Another sample collected in Quebrada Tacagua, in the upper part of the formation, is finer-grained, has more quartz, chlorite, and graphite, and little muscovite.

A specimen from an outcrop near the coast line, in the Río Mulatos, corresponds to one of the dark limestone bands within the lower part of the formation. It consists of about 75% calcite, 10% muscovite, and 15% quartz, with some zoisite, chlorite, graphite, and pyrite.

Tacagua formation.—In the Tacagua valley the top of the calcareous schist formation is exposed near the junction with Quebrada Topo. Here it becomes interlayered with a light green rock made up largely of sericite and epidote. The transition is characterized by the alternation of dark layers of calcareous schist and light layers of sericite-epidote schist.

North of Quebrada Topo, the sericite-epidote schist is 150 to 200 m. thick, but the top of the formation has been eroded. It is the uppermost metamorphic formation observed in the Caracas region. The best exposures are at Tacagua, but it also crops out on the Río Mamo valley and at several places near the coast.

The rock is fine-grained, light green, and uniformly foliated in thin layers. Some white bands are mainly quartz and albite. It is slightly calcareous in the lower part of the section. Quartz veins also occur in this schist but are fewer than in the underlying calcareous schist.

Structurally, the sericite-epidote schist is competent in relation to the calcareous schist. At the contacts, on the flanks of small folds, layers of sericite-epidote schist imbedded in calcareous schist typically develop *boudinage* structure.

This formation was first described by the writer (Dengo, 1947, p. 138). No other mention of it has been found in the literature. No geographic name has been applied to it yet, but, if such a procedure is to be followed, an appropriate name for it is the Tacagua formation.

The mineralogy of the formation indicates that the original material was largely volcanic. The field relations show that it was formerly a sediment. It probably was a volcanic tuff or a sediment made up largely of volcanic ash.

A sample of the sericite-epidote schist from the lower part of the formation, collected at the type locality, consists largely of epidote which, together with zoisite and clinozoisite, accounts for 60% of the rock. Next in abundance is sericite, about 25%; other minerals present are orthoclase, calcite, quartz, chlorite, graphite, and pyrite. The rock is very fine-grained and has well-developed foliation consisting of an alternation of sericite-rich layers with lenticular aggregates of epidote.

A specimen from the upper part of the formation consists mostly of sericite, orthoclase, and epidote and zoisite. Sericite makes up about 70% of the rock, orthoclase about 15 to 20%. There are minor amounts of albite and pyrite. The rock slide does not show any quartz, although in the outcrop there are small quartz veins. The rock is very fine-grained. The orthoclase forms small lens-shaped porphyroblasts and has inclusions of sericite and zoisite.

A sample collected in the Río Mamo, near the engine house of the power plant, is made up of epidote and zoisite which together account for about 15% of the rock, 25% orthoclase, 20% calcite, about 25% sericite and chlorite together, and the rest is albite and pyrite. This specimen is coarser-grained than the others described. The orthoclase occurs as small porphyroblasts in which inclusions of other minerals have been rotated. The sericite and chlorite form small folds and are bent around orthoclase grains.

Cabo Blanco group.—Although the principal object of this paper is the study of the meta-

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morphic rocks of the Caracas region, the sedimentary rocks of Cabo Blanco are discussed briefly for the sake of completeness.

The Cabo Blanco sediments consist mainly of sandstone, with interbedded marly clays and conglomerates. There are at least three distinguishable groups of beds, and a fourth one is questionable. The oldest beds are gray cross-bedded sandstones, which dip about 50° S. Overlying them is a coarser sandstone, cross-bedded, and interstratified with conglomerate. It also dips south but at angles near 20°. In the upper part there is a coarse conglomerate.

Humboldt, Karsten, and Wall considered the Cabo Blanco rocks as Tertiary (Liddle, 1946, p. 528). Martin (1888) collected fossils from Cabo Blanco which he determined as Pleistocene. Kehrer (1939a, p. 1853) has explained that Martin's collection came from a marine Pleistocene terrace and not from the oldest Cabo Blanco rocks. The fairly steeply south-dipping beds are considered by Kehrer as Middle Miocene on the basis of 23 species of mollusks identified by W. P. Woodring. Kamen Kaye (Kehrer, 1939b, p. 704) has suggested that these beds may be younger than Miocene.

Aguerrevere and Zuloaga (1937, p. 11) referred to the Cabo Blanco as Miocene-Pliocene without further statements. Since the writer has made no detailed studies of these beds they are mapped as Miocene-Pliocene. For the same reason the term group has been used instead of formation.

Local Correlation and Stratigraphic Nomenclature

The different problems encountered in the discrimination and correlation of the cartographic units chosen in the mapping of the Caracas region have been pointed out in the descriptions of each formation. Because of the tectonic complexities of the area, the similarity of some of the rocks of one formation with rocks of other formations, and the presence of igneous rocks in several localities, the field discrimination of mapping units becomes rather difficult. Furthermore, the metamorphic facies changes, and the lithologic variations due to inherent changes of sedimentary facies introduce more problems when the discrimination and correlation of formations is attempted.

Two major problems of local correlation have been encountered: (1) the problem of whether or not the limestones of the Zenda member are stratigraphically equivalent to those of the Antimano formation; (2) the correlation of the Peña de Mora gneiss.

Concerning the problem of the limestone units, the Zenda limestone may be stratigraphically lower than the Antimano limestone, or they may be essentially the same zone. The author favors the first alternative on the grounds that the limestones are lithologically different, and that the Zenda member is interbedded in quartz-mica schist, whereas the Antimano limestone is at the contact between the quartz-mica schist and calcareous schist. Since both limestones are lenticular, their stratigraphic position has to be ascertained mainly by their relationships with the adjacent rocks, and this is rather difficult because the quartz-mica schist and the calcareous schist vary greatly in lithology and often resemble each other.

The limestones also differ in their content of MgO. The Zenda type is, on the whole, rich in MgO (*i.e.*, 17.5 per cent at La Guairita), while the Antimano type usually has only a trace of it. This criterion is not completely satisfactory, however, because the difference in MgO may be related to some metasomatic process during metamorphism.

The correlation of the Peña de Mora gneiss is complicated by the fact that it has not been possible, in the Caracas region, to trace it laterally into other rocks. In the region north of Maracay, according to Aguerrevere and Zuloaga (1937, p. 8), one can observe the transition from Las Brisas formation into augen gneiss; hence the Peña de Mora is considered equivalent to the Las Brisas formation. The reasons to think this is true of the Caracas region have been given.

The stratigraphic relationships of the metasedimentary formations of the Caracas region are summarized in Figure 2. This very much simplified diagram is not to be interpreted as showing any structure or as an actual cross section, though the structural names given correspond to the structural features where the relationships shown were observed.

The names introduced into the literature by Aguerrevere and Zuloaga are retained but with the following modifications:

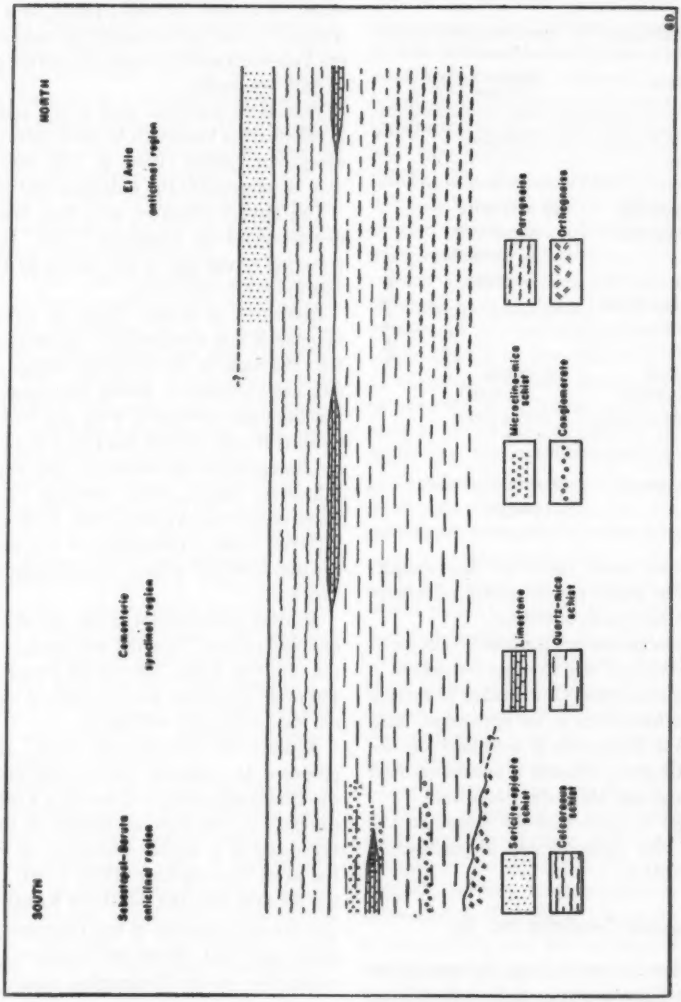

FIGURE 2.—DIAGRAM SHOWING STRATIGRAPHIC RELATIONSHIPS IN CARACAS REGION

(a) Las Brisas has been redefined and considered as consisting mostly of quartz-mica schist with conglomeratic layers, and not as a conglomerate. It has been extended to include the quartz-mica schist above the Zenda member, and below either the Mercedes calcareous schist or the Antimano limestone.

(b) Two new names are proposed—the Antimano formation and the Tacagua formation.

(c) The Caracas group is extended to include the Tacagua formation as its uppermost unit. The Antimano limestome is automatically included in this group because it occurs between the Las Brisas and Mercedes formations.

An attempt to harmonize the names used in this report with those already in existence is shown on Table 4.

TABLE 4.—COMPARISON OF STRATIGRAPHIC NAMES

	This paper	Aguerrevere and Zuloaga (1938)	
Caracas group	Tacagua formation	Not described	
	Las Mercedes formation	Las Mercedes formation Los Colorados member	Caracas group
	Antimano formation		
	Las Brisas formation Zenda member	Las Brisas formation Zenda phase	
	unconformity		
	Sebastopol group	Sebastopol basal complex	

Regional Correlation and Age

The problem of determining the age of the rocks of the Caracas group and of correlating them with unmetamorphosed sediments is one of the most important factors for the understanding of the tectonic history of northern Venezuela and the Caribbean region.

In the Caracas region no identifiable fossils have been found in the metamorphic rocks. The following discussion is based mainly on the literature, considering not only the area studied, but the Cordillera de la Costa and Serranía del Interior as a whole.

Wall (1860, p. 465) introduced the term Caribbean system, later changed to Caribbean series (Wall and Sawkins, 1860), as a general designation for the metamorphic rocks of northern Venezuela and Trinidad. He did not attempt to date the series.

This name has been used in the same sense in reference to Venezuela by most later workers, except for Liddle (1946, p. 72), who uses it only in referring to the Paleozoic schists.

The author disagrees with him because, as demonstrated by Schuchert (1928), the determination of the age of the schists as Paleozoic was the result of an error.

According to Kugler (1936, p. 1441), Cunningham-Craig was probably the first to suggest that the rocks of the Northern Range of Trinidad are Cretaceous, basing the suggestion on the lithologic similarity with the rocks of the Central Range. Kugler has found in the Northern Range lenticular masses of limestone within calcareous schists, with caprinids "similar to those of the well known Stack Rock at Point-à-Pierre, which is considered to be Cenomanian age and identical with the Cogollo limestone of Venezuela."

Another contribution to the age of the metamorphic rocks of Trinidad was made by Hutchison (1939, p. 1234), who found Jurassic fossils. These are the oldest known rocks in the Northern Range that are well dated.

Aguerrevere and Zuloaga (1937, p. 21–22) proposed to correlate the Caracas group with the Cretaceous section of western Venezuela on the basis of lithologic similarities of the formations and of a similar succession of rocks. At the same time Kehrer (1937, p. 60) expressed the opinion that the Northern Range of Trinidad is a continuation of the Venezuelan coastal range, and that, therefore, Cretaceous beds are expectable in the Venezuelan range. He also considered the correlation proposed by Aguerrevere and Zuloaga as possible, and pointed out that there is a transition from metamorphosed to unmetamorphosed Cretaceous sediments between Acarigua and Barquisimeto.

The correlation of the Caracas group with the Cretaceous section has been favored by several geologists. Renz (1942), for instance,

has used it as valid. Bucher (1949) also subscribes to it as the most probable one.

Some geologists, however, think that rocks older than Cretaceous exist in the coast ranges. Hedberg (1942, p. 202) expresses the belief that, in the Paria-Araya area, there are metamorphic rocks equivalent to the Jurassic limestone of the Northern Range of Trinidad. Hedberg (1942, p. 203) considers the proposed correlation of Aguerrevere and Zuloaga possible, but states that the Caracas group may be metamorphosed Triassic-Jurassic.

González de Juana (1947, p. 694), referring to the metamorphics of Paria-Araya and Margarita, favors a pre-Cretaceous age.

Wolcott (1943) and Dusenbury and Wolcott (1949) have found fossils in the metamorphic rocks of the Cordillera de la Costa in two localities. In Quebrada de Cara, near Guarenas, the fossils were identified as possibly Jurassic. Wolcott thought they came from Las Mercedes formation, but later believed that they came from a limestone equivalent to Zenda.

The second locality is in the Quebrada Yeguapo between the towns of Capaya and Caucagua. The fossils came from Los Colorados member of the Las Mercedes formation. Dusenbury identified Foraminifera and Radiolaria from this locality and concluded that the microfauna is Turonian. Dusenbury and Wolcott (1949, p. 23) point out that, if the correlation of the sample with Los Colorados limestone is correct, Los Colorados must be correlated with the Querecual and La Luna, exactly as Aguerrevere and Zuloaga suggested.

Thus the present information on the age of the metamorphic rocks of the Cordillera de la Costa favors a Mesozoic age for most of them. The Caracas group is in part, if not wholly, Cretaceous. The Sebastopol group is pre-Cretaceous, but its age is unknown. Jurassic and Cretaceous rocks exist in the Northern Range of Trinidad, which is very closely related to the Venezuelan coastal range.

Igneous Rocks

Ultramafic Intrusives

General statement.—Along the Cordillera de la Costa and the Serranía del Interior, numerous ultramafic intrusive bodies are found. Within the Caracas region they are relatively small and consist mostly of serpentinites and serpentinized peridotites. The two largest outcrop west of Los Castillitos and east of Río Curucutí, Smaller bodies exist in the valley of the Río Mamo and at Las Adjuntas, near the junction of Río Macarao with Río San Pedro. Several small bodies of highly sheared serpentinite are found along the eastern side of the Valley of Quebrada Tacagua; some are exposed in highway cuts between Caracas and La Guaira. Finally, thin sheets of sheared serpentinite are intruded into the belt of graphitic and calcareous schists that parallels the coast line from Arrecife to El Caribe.

Field relations.—Most of the serpentinites observed have contacts conformable with the foliation of the enclosing gneisses and schists.

The Castillitos intrusion is 2.5 km. long in an east-west direction, and on the average it is between 800 and 1000 m. wide. The thickness cannot be estimated because the overlying rocks, and probably a large part of the serpentinite, have been eroded. At present its maximum thickness must be around 200 m., provided it is a concordant intrusion. The lower contact of this serpentinite is not exposed, but could be located with some accuracy because within a short distance the lithology changes into the banded Peña de Mora gneiss which underlies it. At two places on the northern side of the intrusion, mineral assemblages typical of serpentinite contacts with siliceous rocks were observed. One, near the western end of the serpentinite, consists mostly of chlorite. The other, 1.5 km. to the east, consists of talc and actinolite. According to the relationships elsewhere (Phillips and Hess, 1936), this is a typical example of metamorphic differentiation along contacts between siliceous country rocks and serpentinites. The chlorite is on the gneiss side of the contact, and the talc-actinolite rock on the ultramafic side of the same contact. Judging from the dips of the underlying gneiss near the contacts, the serpentinite seems to be concordant.

The ultramafic body exposed in the valley of the Río Curucutí is the best example of conformable contacts between serpentinites and the foliation of the underlying rocks found in the area. This contact is exposed in a cut on

the old road between Caracas and La Guaira, at a place where a large portion of the serpentinite has been eroded and an inlier of the underlying Peña de Mora gneiss crops out. The eastern limit of the intrusion is poorly exposed, but it seems to be in conformable contact with the gneiss below. The southwestern and northern boundaries of the intrusion are faults. This serpentinite covers a larger area than that at Castillitos. Judging from the field position of both intrusions, they seem to have been originally a single body, perhaps a sill, which was later broken into two portions by a large fault (Pl. 1, section B-B′).

The serpentinite at Río Mamo seems to be conformable with the underlying rock, but the contact could not be found.

At Las Adjuntas the ultramafic intrusive also appears to be concordant. The wall rocks close to the intrusion dip outward, suggesting a lenticular or domical shape.

More or less paralleling the coast line, and intruded into calcareous and graphitic schists of the Mercedes formation, are several small sills or lenses of serpentinite commonly 10–20 m. thick. They are highly sheared, and their contacts with the wall rocks appear to be shear planes, but they are not related to major faults. The present contacts seem to parallel the foliation of the schist.

Along the eastern margin of the valley of Quebrada Tacagua are exposed several small schistose serpentinites. They are all enclosed within schist, but are very close to a major fault (Tacagua fault) which separates the Peña de Mora gneiss from schist in this region. Some are in direct contact with this fault or with minor faults. Their original shape has been much changed by the movements along these faults.

The Curucutí and Castillitos intrusions occur just above the Peña de Mora gneiss, where it is banded, fine-grained, and grades into garnetiferous mica schist. The Mamo mass is underlain by garnetiferous mica schist. The intrusion at Las Adjuntas occurs within the upper part of Las Brisas quartz-mica schist, near the contact with the Mercedes schist. The serpentinites near the coast and along the Tacagua fault are within the Mercedes formation. In general, the larger masses of ultramafics in this region occur as sills at or close to the top of the Peña de Mora formation or its probable stratigraphic equivalent, the Las Brisas formation, and the smaller bodies occur higher in the stratigraphic succession, in the calcareous schists of Las Mercedes formation.

Petrography.—A sample from the Castillitos serpentinite consists largely of fine-grained antigorite and magnetite and a few olivine relics. The antigorite occurs as small lamellae, most of which are subparallel. Magnetite is secondary because it is interstitial and is always associated with the antigorite. Olivine occurs as small irregular grains some of which are partly altered to antigorite. The rock is a serpentinized peridotite or dunite.

One specimen from the wall rock near the contact with the Castillitos intrusion is made up of fine-grained chlorite, with brookite, magnetite, and pyroxene. Some of the chlorite has anomalous interference colors, suggesting that it is penninite. Brookite forms large crystals up to 7 mm. in length. The pyroxene is monoclinic and is partly altered; it is probably chrome diopside.

A sample of the Curucutí serpentinite collected in the Río Curucutí is made up mostly of fine-grained antigorite. This specimen, however, besides having olivine fragments, also has small grains of a monoclinic pyroxene, probably diopside. A mineral of the amphibole group, probably anthophyllite, is common in this rock. Some of the amphibole seems to have developed at the expense of the pyroxene. Secondary magnetite, resulting from the alteration of olivine, exists in association with the antigorite.

Another sample from the Curucutí intrusion, collected at its northern part along the old highway to La Guaira, consists of about 75% antigorite with subparallel orientation. Small relict grains of olivine form about 20% of the rock. There are also small grains of diopside and secondary magnetite. The rock is a serpentinized peridotite. Its chemical analysis and norm are given in Table 5.

Samples of the Mamo intrusion show less advanced serpentinization. One specimen from the lower part of the intrusion consists of about 65% olivine, altered in part to antigorite and magnetite. Antigorite occurs interstitially around olivine grains forming a mesh structure, or in veinlike forms. Some carbonate is also present. Pebbles containing chrome diopside have been found near this intrusion and seem to have been derived from it, although the chrome diopside has not been found in place.

The small bodies of ultrabasic rocks have been more thoroughly serpentinized than the larger ones. Two samples from the occurrences at Plan de Manzano consist almost solely of antigorite. One of them has, besides antigorite, some secondary magnetite and a carbonate mineral, probably magnesite. Antigorite occurs as very fine-grained blades. Another one from the same locality consists only of antigorite, which occurs in elongated crystals from 0.1 to 1.5 mm. in length. The crystals are optically negative, with a 2V approximately at 40°, weak birefrigence, parallel extinction, dispersion of optic axes is $r > v$, and are length fast. The chemical composition of this mineral is given in Table 6, together with the composition of antigorite from Antigoria Valley, Italy (Niggli *et al.*, 1930, p. 28) for comparison.

The serpentinite at Las Adjuntas is the only one, within the area mapped, in which chrysotile has been found. Farther west, near San Pedro, State of Miranda, there are ultramafic bodies in which chrysotile is fairly abundant. A sample from Las Adjuntas is made up mainly of fine-grained antigorite, with chrysotile, chlorite, and magnetite. The chrysotile occurs as thin veinlets which are older than the antigorite, because they are in part replaced by this mineral. Magnetite is secondary and is associated with some chromite.

TABLE 5.—CHEMICAL ANALYSIS AND NORM OF CURUCUTÍ SERPENTINITE

SiO_2	40.55	C	1.07	
Al_2O_3	1.80	Pc Ab (8.5)	.16	2.11
		Pc An	1.95	
Fe_2O_3	3.66	Hy En	30.00	30.79
		Hy Fs	.79	
FeO	3.19	Ol Fo	49.00	50.53
MgO	40.05	Ol Fa	1.53	
CaO	.41	Mt	5.34	
Na_2O	.02	Cm	.45	
K_2O	.00	Fe/Mg = 1/15		
H_2O+	9.47	Sp. G. at 21°C 2.79		
H_2O-	.06	Analyst: E. Chadbourn		
TiO_2	.02			
Cr_2O_3	.37			
MnO	.11			
NiO	.14			
Total	99.85			

TABLE 6.—CHEMICAL ANALYSIS OF ANTIGORITE

	Antigorite from Plan de Manzano	Antigorite from Antigoria Valley
SiO_2	43.60	41.58
Al_2O_3	1.03	2.60
Fe_2O_3	.90	—
FeO	.81	7.22
MgO	41.00	36.80
CaO	.05	—
Na_2O	.01	—
K_2O	.03	—
H_2O+	12.18	12.67
H_2O-	.08	
TiO_2	.01	—
Cr_2O_3	.02	—
MnO	.04	—
NiO	.16	—
Total	99.92	100.87

Sp. G. at 25.5°C 2.585
Analyst: L. C. Peck

Metamorphosed Basic Igneous and Related Rocks

General statement.—Under the general term of metamorphosed basic igneous rocks are included eclogitic amphibolites, garnet amphibolites, epidote amphibolites, and glaucophane schists, thought to be mainly metamorphic equivalents of igneous rocks. Although there are fundamental differences among these rock types, their field occurrence points toward a somewhat related origin; it therefore seems appropriate to discuss them together.

Although the occurrence of these rocks is well known to geologists acquainted with the Caracas region, there are only a few published descriptions of them. Humboldt (1804, vol. III, p. 49) mentioned a rock near Antimano which he called "Ur-Grünstein," consisting of amphibole, laminar feldspar, and garnet. Later Wall (1860, p. 462) mentioned the occurrence of eclogites near Caracas and near Puerto Cabello. Lamare (1927, p. 143) has described two amphibolites from the Cordillera de la Costa, one near Guayas and the other near Caucagua.

Amphibolites and eclogitic amphibolites.—In the Caracas region the most abundant rocks of the type under discussion are garnet amphibolites and epidote-garnet amphibolites, but some eclogitic amphibolites have been found. By eclogitic amphibolite is meant a rock whose principal minerals are an amphibole, usually hornblende, and garnet, with a small proportion of the pyroxene omphacite. No true eclogites, that is, rocks which consist mainly of garnet and omphacite, have been found in the region.

The largest mass of garnet amphibolite occurs north of Caracas, at Infiernito. This place is quite heavily wooded, and consequently the rocks are poorly exposed. Garnet amphibolite is also exposed near the western limit of the area mapped, at the junction of Quebrada Yaguara and Río Mamo. Still further west there are extensive bodies of amphibolite, particularly north of the town of Carayaca. Other well-known localities are those near Antimano which extend to the west, and those north of La Florida. Good outcrops of amphibolite and eclogitic amphibolite may be seen along the road and railroad at Plan de Manzano. Besides these localities, very small bodies of amphibolite are also present along the Tacagua and

Topo valleys, and on the seaward slopes of the Sierra del Avila.

The field relations at Infiernito are not clear. Garnet amphibolites are in association with limestone and calcareous schist in the western part, but toward the east they are immediately above banded gneiss. The amphibolite has a well-developed planar structure due to alternation of bands of garnet and amphibole, and to subparallel arrangement of the amphibole crystals. In hand specimen the rock is dark green, fine-grained, and has small garnet porphyroblasts. Several thin albite veins crosscut the foliation of the amphibolite in this area. The thickest one observed reaches 15 cm. and consists of albite and actinolite; the latter is closer to the wall rock and with crystals developed perpendicular to the walls. Thinner veins contain only albite.

At Mamo the amphibolite is well foliated, and the garnet commonly is arranged in layers. The foliation is conformable with that of the underlying schists. Albite and albite-actinolite veins also occur within the amphibolite but do not continue into other rocks.

At La Florida, Carapita (Humboldt's locality 1 kilometer east of Antimano), and north of Antimano, the amphibolite masses are rather small as compared with those at Infiernito and Mamo. Their contacts with the country rocks are concordant, indicating that the amphibolite masses are tabular or lenticular. The smaller bodies observed are definitely lenticular, and in several cases there is evidence that this shape is the result of segmentation of larger bodies in a boudinage structure.

In a boulder in Quebrada Tacagua a 40-centimeter thick amphibolite interlayered with limestone shows the amphibolite separated into lenticular fragments around which the limestone has flowed. Shadow zones at the ends of the amphibolite fragments or lenses are filled by a pegmatitic albite-actinolite rock. Wegmann (1932) has traced several stages in the formation of boudinage structure in amphibolites; the final ones show the formation of pegmatitic material in strain shadows as at Tacagua.

Some of the amphibolites in this area are associated with limestones. Eclogites and amphibolites are associated with limestones near Kornstadfjord in Norway (Eskola, 1921, p. 19), in the Erzgebirge in Germany (Fiedler, 1936, p. 471), in the Val d'Aoste in Switzerland (Bonney, 1886, p. 4), and in the vicinity of Glenelg, Scotland (Alderman, 1936, p. 489). In the Caracas region most of the garnet amphibolites and eclogitic amphibolites occur near limestones, but some have been found within the Peña de Mora gneiss and within the Mercedes schist. Eskola (1921, p. 19) thinks there is no genetic connection between the eclogites and limestones in Norway, and Alderman (1936, p. 489) believes that the association in Scotland is merely fortuitous. In the Caracas region the association of those rocks also seem to be fortuitous.

Petrography.—The following descriptions of rocks correspond to the most common types of amphibolites found in the region. Two of the smaller amphibolite bodies are considered in more detail to show relationships which are more difficult to study in the larger masses.

The amphibolite in Infiernito has not been studied in detail; a sample of the most common type of rock found there consists of garnet, amphibole, zoisite, clinozoisite, with minor amounts of pyroxene, quartz rutile, apatite, muscovite, and pyrite. Garnet forms about 30% of the rocks and occurs as fresh idioblastic crystals which range in size from 0.25 to 1 mm. A larger garnet, not from the same specimen but from the same locality, has a specific gravity of 3.92 and an index of refraction of 1.782, which correspond to the composition of almandine-pyrope. Amphibole forms about 50% of the rock. There are two amphiboles; one is a light-green actinolitic hornblende which is more abundant, and the other is glaucophane. Zoisite is more abundant and occurs in larger crystals than clinozoisite, reaching 2.5 mm. A pyroxene, partly altered to hornblende, exists in minor amounts. It is optically positive, slightly pleochroic, has a 2V of approximately 65°, and the dispersion of optic axes is $r > v$, all of which are properties of omphacite. The rock is an eclogitic amphibolite.

At Carapita the amphibolite has been interpreted as a concordant body, although the field relations are obscure. This sill-like body is about 15 meters thick. Two samples of it have been studied, one from the upper part, and one from the lower part.

The specimen from the upper part, a garnet amphibolite, consists of about 20% garnet, about 50% actinolitic hornblende with some glaucophane, and about 20% zoisite and clinozoisite, with some epidote, albite, quartz, rutile, and magnetite-ilmenite partly altered to leucoxene. The garnet is in part replaced by clinozoisite and occurs in crystals up to 2 mm. in diameter. The amphibole occurs in small elongated crystals of xenoblastic habit which have an extinction angle of approximately 12°, and a 2V of about 85°; it is in part replaced by a

light-blue glaucophane. The specimen from the lower part is an epidote amphibolite which consists largely of xenoblastic actinolitic hornblende, about 60%, epidote, clinozoisite, with chlorite, quartz, albite, and ilmenite-magnetite. Chlorite occurs in aggregates which are probably pseudomorphs after

type of rock that makes up the bulk of it, is an epidote amphibolite consisting of about 65% light-green actinolitic hornblende with a small amount of glaucophane, both occurring as xenoblastic elongated crystals, about 25% of epidote, and a little zoisite, albite, sphene, chlorite, apatite, and mag-

TABLE 7.—CHEMICAL ANALYSES OF AMPHIBOLITES

	1*	2*	3*	4*	5*	A	B	C
SiO_2	50.51	47.64	49.41	49.69	49.61	46.44	45.96	49.06
Al_2O_3	13.48	15.43	15.12	14.78	14.92	12.60	12.77	15.70
Fe_2O_3	1.80	2.30	4.61	5.14	6.92	6.78	6.00	5.38
FeO	10.43	7.11	4.29	4.23	3.87	5.18	8.14	6.37
MgO	7.39	9.18	9.30	9.36	7.63	4.42	4.87	6.17
CaO	8.86	11.89	10.83	9.50	8.88	11.52	5.99	8.95
Na_2O	3.29	1.46	2.86	2.67	3.87	2.91	6.06	3.11
K_2O	.21	.20	.11	.81	.36	1.65	.98	1.52
H_2O+	2.02	3.32	2.38	2.65	2.24	1.78	3.42	1.62
H_2O-	.05	.24	.15	.24	.14	.16	.07	—
TiO_2	1.34	1.03	.71	.77	1.19	2.84	4.68	1.36
P_2O_5	.11	.09	.07	.07	.10	—	—	.45
MnO	.19	.15	.13	.14	.14	—	—	.31
CO_2	—	—	—	—	—	3.88	1.37	—
Total	99.68	100.04	99.97	100.05	99.87	100.16	100.31	100.00
Sp. G. at 22°C	3.168	3.048	3.138	3.118	3.19+			

* E. Chadbourn, Analyst.

1—Garnet amphibolite (top), Carapita.

2—Epidote amphibolite (bottom), Carapita.

3—Epidote amphibolite (center), Antimano.

4—Epidote-glaucophane amphibolite (bottom), Antimano.

5—Epidote-glaucophane schist, Carapita.

A—Epidote-glaucophane rock, Brussoley, Wallis (Woyno, 1912, p. 196).

B—Epidote-glaucophane schist, Louriter, Valde Bagnes (Woyno, 1912, p. 155).

C—Average basalt (Daly, 1933, p. 17).

garnet. Albite is poikiloblastic, having amphibole inclusions, and is found only in minor amounts (Tables 7, 8).

The amphibolite mass .5 km. north of Antimano is here interpreted as a tabular concordant body, about 20 to 25 m. thick. In this case the lower contact is well exposed, and the amphibolite overlies a thin quartzite layer.

A sample from its upper part is an epidote-garnet amphibolite. It consists approximately of 60% glaucophane and actinolitic hornblende in about equal amounts, with 25% garnet and about 10% epidote, with minor amounts of clinozoisite, sphene, and magnetite ilmenite. The garnet is partly replaced by chlorite and epidote, and the ilmenite-magnetite is altered to leucoxene. The rock is fine-grained, the average size of the crystals being about 0.25 mm. A sample from the central part of the amphibolite mass, which represents the

netite. The actinolitic hornblende is negative, has an approximate 2V of 80°, and an extinction angle of about 16°. It is in part replaced by glaucophane. Epidote occurs in aggregates of crystals generally surrounded by larger amphibole crystals, resembling the ophitic texture of diabase (Tables 7, 8).

The lower part of the mass north of Antimano is an epidote amphibolite or an epidote-glaucophane rock. It is made up of about 65% glaucophane, 25% epidote, with subordinate amounts of actinolitic hornblende, chlorite, sphene, and magnetite. The glaucophane occurs as small elongated crystals with an approximate extinction angle of 6°; β = 1.635. It is pleochroic with Z dark blue lavender, Y light blue, and X nearly colorless. Chlorite is rare, but when present it forms aggregates which are possibly pseudomorphs after garnet (Tables 7, 8).

In both the Carapita and the Antimano examples there are some noteworthy mineralogical and chemical changes. Garnet occurs

at the top of the amphibolite masses. Chlorite pseudomorphs indicate that originally garnet also occurred in lower parts, but in smaller quantities. Suzuki (1930, p. 39) has described a similar case in Japan. Another change of mineralogy is the decrease of actinolitic hornblende and increase of glaucophane in the lower part of the amphibolites, particularly that north of Antimano. This change does not seem to depend on the amount of Na_2O because the rock richer in glaucophane is somewhat poorer in that constituent. It may be related, however, to an increase in Fe_2O_3 and decrease in FeO, which is the only chemical change consistent from top to bottom, in both cases under consideration. It may be that the oxidation of iron is accompanied by the development of glaucophane at the expense of actinolitic hornblende. A somewhat similar relation of increasing glaucophane toward the base of a basic glaucophane schist mass has been described by Freeze (1942, p. 38–40). In this case, however, the glaucophane seems to have formed at the expense of augite.

Samples from Plan de Manzano are garnet amphibolites and epidote-garnet amphibolites similar to some of the rocks already described. One sample, however, collected near the place where the railroad to La Guaira crosses the Quebrada Ojo de Agua, is an eclogitic amphibolite.

TABLE 8.—NORMS OF AMPHIBOLITES FROM ANALYSES IN TABLE 7

		1	2	3	4	5
Q		—	.21	—	.21	—
Pc	Or	1.11	1.11	.56	4.73	1.94
	Ab	27.77	12.31	24.10	22.54	32.49
	An	20.85	35.15	28.08	25.99	22.80
Di	Wo	9.28	9.68	10.44	8.70	.17
	En	5.00	6.30	8.25	6.90	.15
	Fs	3.96	2.27	1.06	.79	—
Hy	En	10.70	16.60	13.60	16.50	7.70
	Fs	9.50	7.05	1.72	1.78	15.54
Ol	Fo	1.49	—	1.82	—	—
	Fa	1.73	—	.30	—	—
Hem		—	—	—	—	.24
Il		2.43	1.98	1.37	1.44	2.13
Mt		2.55	3.25	6.73	7.42	9.62
Ap		.34	.34	.17	.17	.34
Fe/Mg		1/1.18	1/2.2	1/2.6	1/2.6	1/2

This rock consists of 45 to 50% of light-green actinolitic hornblende, about 25% garnet, 15% pyroxene, with zoisite, quartz, muscovite, rutile, and pyrite. Hornblende occurs as xenoblastic crystals as large as 5 mm. in length. The pyroxene is light green, particularly in hand specimen, and occurs in crystals with irregular borders, the largest being about 1 mm. in cross section. Its optical properties are: 2V near 67°, extinction angle near 41°, dispersion of optic axes $r > v$, positive sign, low birefringence, and β is 1.676, all of which correspond to omphacite. Zoisite is fairly abundant and belongs to the nonferric variety. The rock is an eclogitic amphibolite on account of the presence of omphacite. It occurs as bands in association with garnet amphibolites without pyroxene, all of which are within calcareous quartz-mica schist.

Glaucophane schists.—Besides the occurrences of glaucophane in the amphibolites, there are other rocks which consist largely of this mineral.

A small mass of glaucophane schist in Carapita outcrops along the road to the limestone quarries, about .5 km. from the intersection with the highway to Antimano. It occurs interbedded with, and infolded into, calcareous quartz-mica schist. The rock in hand specimen is fine-grained, finely banded, and light blue. The field relations suggest that it was originally a sedimentary rock, perhaps a tuff, now changed to an epidote-glaucophane schist.

A sample of this rock from Carapita in thin section is an aggregate of glaucophane and epidote. Glaucophane makes up about 60% of the rock and occurs as small elongated crystals. It is optically negative, has an extinction angle of approximately

12°, and the β index of refraction is 1.635. Epidote forms lenticular layers alternating with the glaucophane, and occasionally occurs as small porphyroblasts. It forms about 30% of the rock. Small amounts of clinozoisite occur in association with the epidote. Sphene is fairly abundant. Other minerals are chlorite, muscovite, apatite, and magnetite (Tables 7, 8). The mineralogical resemblances of this rock to the lower part of the amphibolite north of Antimano are noteworthy. The facts that they occur in the same area and are enclosed within the same kind of wall rocks suggest that they may have originated in a similar way.

Other glaucophane schists have been found in the upper part of the Peña de Mora gneiss. They occur as small lenticular masses, which may be observed in the cuts of the highway to La Guaira, near kilometer mark 23, and also half way between kilometers 18 and 19 on the railroad.

A sample from one of these lenses consists of about 60% glaucophane and 30% garnet, with hornblende, pyroxene, chlorite, epidote, rutile, and magnetite. The garnet occurs in crystals about 2.5 mm. in diameter and is partly altered to chlorite. Pyroxene, present in very small amounts, is optically positive, has an approximate 2V of 65°, and low birefringence. It is probably diopsidic augite. Glaucophane occurs in elongated crystals which are pleochroic with Z = lavender blue, Y = light blue, and X = nearly colorless. It is optically negative, the β index of refraction is 1.637, and the extinction angle is approximately 8°. Hornblende occurs in small amounts, mainly between crystals of garnet and glaucophane. Rutile is fairly abundant. This rock differs from the glaucophane schist from Carapita merely in the presence of garnet and the smaller amount of epidote. It probably corresponds to a higher grade of metamorphism (Harker, 1939, p. 294). Other specimens from near-by rocks are similar to it but have less garnet and more epidote.

Acid Intrusive Rocks

The Sebastopol gneiss has been described as consisting at least in part of metamorphosed granitic rocks. There are other acid igneous rocks in the Cordillera de la Costa much younger than the Sebastopol gneiss, because they intrude the Caracas group. Toward the western part of the Cordillera there are more extensive granite intrusions, as for example between Puerto Cabello and Valencia, near the town of La Trincheras, where there is a granite younger than the metamorphic rocks (López, 1942, p. 8).

In the streams that descend from the Naiguatá Peak there are boulders of granodiorite, but this rock has not been found in place. The peak consists of gneiss, considered to be Peña de Mora formation. Possibly the granodiorite is exposed only in small apophyses of a larger intrusion which does not reach the surface.

Petrology and Metamorphism

General Statement

In the discussions of the stratigraphic sequence and the metamorphosed igneous rocks, the field relations and petrographic characteristics of the rocks of the Caracas region have been described. No attempt has been made to interpret either the conditions of metamorphism or the origin of the rocks found. The following discussion treats briefly such petrologic problems as the metamorphic facies and the possible origin of some rocks.

Metamorphic Facies

Facies concept.—In modern metamorphic petrology the concept of mineral facies, first initiated by Goldschmidt and developed by Eskola (1920), has been stressed because it gives an understanding of the mineral assemblages which, for a given bulk chemical composition, may form under varying conditions of temperature, stress, and confining pressure. This concept may be correlated with that of metamorphic zones used by Harker (1939) and with that of metamorphic grade as defined by Tilley (1924). There is enough information available on the mineral facies (Eskola, 1939; Turner, 1948) to permit comparison of the mineralogical assemblages of newly studied areas with typical metamorphic facies assemblages, and to establish a comparison as to grade of metamorphism.

Greenschist facies.—The greenschist facies of Eskola corresponds to the chlorite and biotite zones of Harker for pelitic schists, and includes rocks deformed under low temperature and moderate pressure.

Rocks of the Tacagua schist, consisting mostly of assemblages in which epidote, sericite, and albite predominate, belong to this facies. The calcareous schist or Las Mercedes formation in which muscovite, chlorite, and quartz occur are also in the greenschist facies, and so is the Antimano limestone with such minerals as actinolite and epidote. No mineral changes

have been found within these rocks that would indicate a change toward a higher facies. The upper part of Las Brisas formation and the Zenda limestone in the southern portion of the Caracas region also belong to the greenschist facies. Limestones with albite, microcline, and quartz, such as the Zenda, are included in this group (Turner, 1948, p. 95). The talc-actinolite-chlorite mineral association found at the contact of the serpentinites has also been formed under the physical conditions of the greenschist facies.

Among the rocks of igneous origin the ultramafics, now largely altered to chrysolite and antigorite, are placed by Turner (1948, p. 98) in the greenschist facies (muscovite-chlorite subfacies). Those altered to antigorite only probably belong to a higher grade of metamorphism.

Albite-epidote amphibolite facies.—The albite-epidote amphibolite facies of Turner (1948, p. 88–92) corresponds to the epidote amphibolite facies of Eskola (1939, p. 355–356) and to the almandine zone of pelitic schists. It includes rocks which have been metamorphosed under conditions of moderate temperature and moderate pressure.

In this facies quartz-bearing rocks with excess K_2O are converted into schists with quartz, microcline, albite, biotite, and muscovite. Quite possibly a portion of Las Brisas formation corresponds to this facies. However, similar asemblages may be found in the greenschist facies. Microcline porphyroblasts may also form as the result of K_2O metasomatism, but in the present example this does not seem to be the case.

The marbles found in the upper part of the Peña de Mora gneiss belong to this facies. Minerals like diopside and tremolite indicate that the original rock was a magnesian limestone low in SiO_2 (Turner, 1948, p. 91). If this marble is equivalent to the Zenda limestone, as has been postulated, it indicates a higher grade of metamorphism in the northern part of the Caracas region.

Amphibolite facies.—This facies corresponds to part of the almandine zone, and to the kyanite and sillimanite zones of pelitic schists—that is, it includes rocks formed under moderate pressure and temperature, but higher than those under which the albite-epidote amphibolite facies was formed.

Las Brisas formation in the northern part of the Caracas region belongs to this facies and is interpreted as intermediate between the quartz-mica schist and the augen gneiss. The augen gneiss has much magmatic material with it so that the garnetiferous schist may have formed under the influence of heat supplied by the invading magma. This kind of rock may withstand fairly high temperatures before any new index mineral indicative of a higher facies appears (Harker, 1939, p. 224).

If we consider the schist of Las Brisas formation essentially as an isochemical rock, the facies changes described indicate an increase of metamorphic grade from south to north.

The rocks of igneous origin which have been metamorphosed under conditions of the amphibolite facies are the amphibolites and garnet amphibolites already described. The common presence of epidote and zoisite in these rocks may be explained by a sufficiently high CaO/Na_2O ratio (Turner, 1948, p. 82). According to Wiseman (1934, p. 357) amphibolites without garnet belong to low-grade metamorphism, corresponding to the epidote-albite amphibolite facies. Those amphibolites described in the Caracas region which do not have garnet have probably undergone retrogressive changes in which chlorite pseudomorphs replaced the garnet.

The chemical analyses of the amphibolites correspond to diabase or basalt (Table 7), and their mode of occurrence strongly indicates an igneous origin for most, if not all, of them. The thin amphibolite layers may have been originally volcanic tuffs. The changes which have taken place in the metamorphism of a diabase into amphibolite are as follows: augite of the diabase goes into hornblende, olivine mixes with the anorthite molecule of the basic plagioclase to form garnet, and the albite molecule crystallizes as such (Grubenmann and Niggli, 1924, p. 404). Possibly part of the albite molecule, or the soda derived from it, goes into the sodic amphiboles.

The eclogitic amphibolites associated with the garnet amphibolites were probably formed under the conditions of this facies and not under those of the eclogite facies. It has been suggested (Dengo, 1950) that these rocks may have been formed metastably under conditions of medium-grade dynamothermal metamor-

phism, and not necessarily under conditions of high-grade metamorphism.

Glaucophane schist facies.—Eskola (1939, p. 367) considers the glaucophane schist as a separate facies which may form at fairly low to medium temperatures and at higher pressures than the amphibolite facies. Turner (1948, p. 100) includes glaucophane schists within the greenschist and the albite-epidote amphibolite facies.

Washington (1901), Woyno (1912), Suzuki (1930), Freeze (1942), and Taliaferro (1943) have studied cases of glaucophane schists derived from both igneous and sedimentary rocks. Washington separated basic and acid glaucophane schists on the basis of the SiO_2 content and other minor chemical differences. Taliaferro (1943, p. 161) has criticized this division because it was not based on enough chemical analyses. However, the author has compared some more recent analyses with Washington's groups, without attempting a complete survey, and it seems to him that this classification, perhaps with some modifications, may be quite useful. Washington stated that in all basic glaucophane schists FeO uniformly surpasses Fe_2O_3. This fact does not seem to apply to all cases. The glaucophane rocks from the Caracas area, and some of those described by Woyno (1912), which on the basis of their SiO_2 content are basic schists, show the reverse relationship between FeO and Fe_2O_3. In general the basic glaucophane schists are epidote-glaucophane rocks which have resulted from the metamorphism of basic igneous rocks and basic tuffs, while the acid type includes quartz-glaucophane schists derived apparently from the Na_2O enrichment of siliceous sediments.

Suzuki (1939, p. 509) and Taliaferro (1943, p. 168) have studied cases in which glaucophane rocks were formed at the upper contacts of ultramafic igneous rocks, and they ascribe them to pneumatolytic action with enrichment in Na_2O. Although in the Caracas region glaucophane schist has not been observed in contact with ultramafic rocks, they may have been formed as the result of permeation by solutions coming from concealed ultramafic masses, because such rocks are common in the region. However, it seems more probable that these glaucophane schists are products of dynamothermal metamorphism of basic igneous rocks and their tuffs. During the metamorphism there may have been permeation by solutions, but it does not seem necessary to call for an enrichment in Na_2O to explain the formation of the glaucophane. According to Brière (1920, p. 175), in metamorphic rock, highly sodic pyroxenes and amphiboles may form in a medium relatively poor in alkalies, when the CaO is present in metasilicates and not in feldspars.

Origin of the Augen Gneiss

In the description of the Peña de Mora gneiss it has been noted that the lower part of it has augen structure, and has been injected, *lit-par-lit*, by aplite veins. The aplites are more abundant in the lowermost parts of the formation. It has been also stated that many field observations favor a correlation of all, or a large part, of the Peña de More gneiss with the Las Brisas conglomeratic quartz-mica schist. This means that, to explain the formation of the augen gneiss, it is necessary to account for a process by which a quartz-mica schist can be enriched in feldspars.

Fenner (1914), in studying *lit-par-lit* injection gneisses in New Jersey, concluded that they originated by injection of a thinly fluid granitic magma, which was a dilute portion of an advancing larger body of granite magma. He has shown that it is possible to have granitic magma of enough fluidity and that it can migrate along the planes of weakness of pre-existing rocks for long distances.

Although in the gneisses described by Fenner the injection seems to have been more intensive than in the Caracas region, a similar explanation would fit well the relations found in the Peña de Mora gneiss. Because the Sierra del Avila, where the gneiss is exposed, is only partly dissected, the relations of the gneiss to a possible underlying granitic mass cannot be seen. The transition from augen gneiss to banded gneiss probably marks the boundary of the zone permeated by solutions of granitic origin. The lower part of the formation is then a mixture of a schistose rock, originally of sedimentary origin, and aplite injections—that is, a migmatitic gneiss.

In the discussion on Regional Deformation, it is shown that the Peña de Mora gneiss is in an area where the earth's crust has undergone

thickening during a period of orogenesis. Eskola (1933, p. 12) has suggested that thickening during orogenesis results in reheating and partial fusion of the crust. During the remelting of silicate rocks, the first part to remelt is of granitic composition, and is squeezed up and injected into overlying rocks. This is consistent with the opinion of Kennedy and Anderson (1938, p. 31, 78), who think that during orogenesis a thickened granitic layer of the earth's crust may fuse and give rise to granite and granodiorite intrusions which are preceded by a zone of migmatization. Possibly the aplite injections are in the zone of migmatization related to an underlying granitic or granodioritic mass.

In this short discussion the term granitization has been purposely avoided because of the different connotations that it involves.

Quartz Veins

Throughout the rocks of the Caracas group quartz veins are very abundant. In general they are more numerous toward the upper part of the group, particularly in the graphitic portion of the Las Mercedes schist. The largest quartz veins have been observed within Las Brisas and Peña de Mora formations. Most of them occur along foliation planes, but a few cut across the foliation.

There are two possible explanations of the origin of the quartz veins. They may be of hydrothermal origin, related to the aplite veins in the Peña de Mora formation, or they may have been formed by lateral secretion of quartz from the country rocks during metamorphism. Some field facts seem to favor the second interpretation. The graphitic schist is separated from those rocks that have been injected by igneous materials by a great thickness of other rocks in which quartz veins are much less abundant. The veins in the graphitic schist occur as small lenses many of which are located in the crests of small folds and in places where differential movements in the schist have formed low-pressure areas. If these veins were of igneous origin they should be more abundant closer to the zone of aplitic injections.

Read (1934, p. 325–326) mentions several localities where innumerable stringers of quartz occur in pelitic rocks, in a manner similar to those under consideration. He concluded that the quartz veins originated by a process of endogenous secretion which may occur even at low grades of metamorphism.

The foregoing interpretation of the origin of quartz veins is suggested for those within the Mercedes schist. Other quartz veins, such as those within the Peña de Mora gneiss, may be of hydrothermal origin.

Summary of Petrology

Rocks of the Caracas region, and in general of the Cordillera de la Costa, have been affected by dynamothermal metamorphism. The deformation occurred under tangentially directed stress with accompanying invasion of granitic or granodioritic magma. A succession of rocks consisting of arenaceous, calcareous, and pelitic sediments, and basaltic igneous rocks and their tuffs, was metamorphosed into gneisses, schists, marbles, and amphibolites. Ultramafic igneous rocks emplaced probably at the beginning of the deformation period were also affected by metamorphism. Much of the rock is of mixed origin, consisting of sedimentary and magmatic materials. The rocks were subjected to differential movements and were recrystallized under conditions of low- and medium-grade metamorphism, resulting mainly in mineralogical assemblages of the greenschist and amphibolite facies. The metamorphism was of higher grade toward the north.

Structural Geology

Metamorphic Structures

Foliation.—At times the terms foliation and schistosity have been used in geologic literature with different meanings, and at other times synonymously. The author prefers to use them according to the following definition (Turner, 1948, p. 275):

> "Foliation and schistosity cover all the megascopically conspicuous parallel fabrics of metamorphic origin which impart definite fissility to the rocks in which they occur."

This use of the terms has the advantage of being only descriptive and does not involve any genetic implications.

It is believed that in the Caracas region the foliation of the metamorphic rocks is parallel

or essentially so, to original bedding. The field facts that support the idea of bedding foliation are:

(1) The foliation parallels layers of pebbles in Las Brisas formation and quartzitic layers in Las Brisas and Peña de Mora formations.

(2) Formational contacts such as those between limestones and other rocks, and that between Las Mercedes and Tacagua formations, are conformable with the foliation of the rocks on both sides.

(3) At several places where the Los Colorados limestone member and the Mercedes-Tacagua transitional layers are deformed in small folds, the foliation of the rocks remains parallel to the layering along all the parts of the folds.

Occasionally, foliation cutting across structures that resemble original bedding has been observed, but this is not common and seems to be always in areas of greater deformation such as the anticlinal crests of incompetent rocks like the Mercedes schist.

Bedding-plane foliation is a controversial subject because, while in several regions the field information points toward its existence, a satisfactory explanation has not been given to account for it. Harker (1939, p. 204) suggests that this type of foliation is a result of segregation, during metamorphism, of certain minerals along the sedimentary bedding planes. Turner (1941) thinks it is the result of metamorphic differentiation during which there has been development of bands of different mineral composition resulting in what he calls pseudostratification. Sander (Turner, 1948, p. 176) thinks that pre-existing *s* surfaces such as stratification exert an influence in the development of slip planes during deformation. These planes have low resistance to shearing stress, and, even if they are inclined at considerable angles to the planes of maximum shearing stress, componental movements are controlled by them.

Noble and associates (1949, p. 331–333) explain the foliation parallel to bedding around crests of folds as the result of orientation of minerals parallel to slip planes, in low-grade metamorphic rocks.

Now, if it is considered that after the componental movements have commenced following pre-existing *s* surfaces there is permeation by solutions, these will migrate more easily along such surfaces. Raguin (1946, p. 98) considers that slip surfaces are favorable for migration of solutions. Griggs (1940), on the basis of his experimental work, concludes that permeation of rocks by solutions may be the principal condition for plastic flow of rocks during the metamorphism. Injection of liquid material during the formation of *lit-par-lit* gneisses would also be guided by pre-existing slip surfaces.

If the crystallization continues after the deformation has stopped (post-tectonic crystallization), the *s* surfaces might become accentuated. This is the so-called mimetic crystallization, which reproduces pre-existing anisotropy of a rock.

The crystallization of the rocks of the Caracas group has taken place contemporaneously with their deformation. Microstructures indicate that rotation of grains has occurred during their crystallization. These same rocks in the field have been interpreted as having bedding-plane foliation. Consequently, any explanation for the foliation has to consider componental movements along original bedding planes, with simultaneous crystallization, resulting in the development of platy minerals oriented more or less parallel to the planes.

Lineation.—Two common types of lineation have been found, pencil lineation and microcorrugations. The first kind is less common. It has been observed in the Sebastopol gneiss and in the Peña de Mora gneiss, on the crests of both large and small anticlines. This lineation is parallel to the axes of folds—that is, to the *b* axis of the co-ordinate system of orientation. The occurrence of pencil lineation is common in metamorphic terrains as a result of the combined effects of plastic flow and flexure on the crests of anticlines and troughs of synclines (Buddington, 1939, p. 310).

The most conspicuous lineation, however, is that due to microcorrugations developed in the foliation surfaces, best observed in the schists. This lineation also parallels or approximates the orientation of the *b* axis. In a few cases this linear structure departs from its usual position and forms high angles with the strike of the foliation.

Occasionally linear structures consisting of grooving on the foliation due to slippage along this surface occur at right or nearly right

angles to its strike. This may be called *a*-axis lineation. Wherever it has been observed, it is superposed on the *b*-axis lineation.

from N.20°E. to N.20°W. and dip from 70°N. and S. to vertical (Dengo, 1947, p. 144). In the incompetent formations, such as the Mercedes

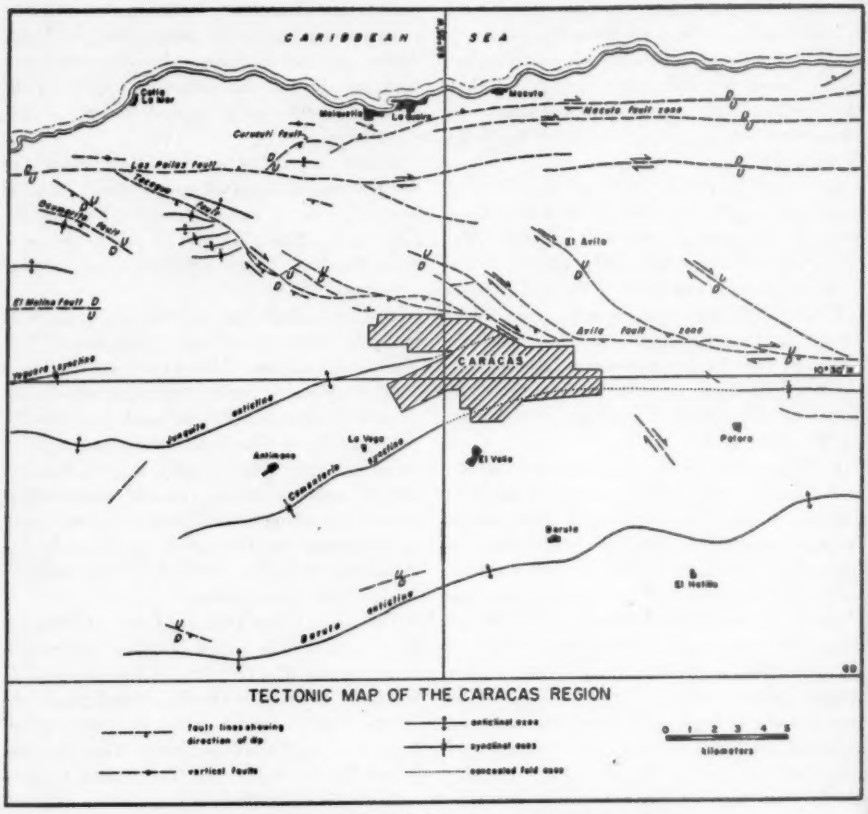

FIGURE 3.—TECTONIC MAP OF THE CARACAS REGION

If, as assumed, the componental movements accompanying metamorphism have occurred along the planes of the present foliation, the *b*-axis lineation probably formed normal to the direction of movement. This interpretation is supported by the position of the drag folds.

Joints.—In the competent formations such as the Sebastopol and Peña de Mora gneisses and in the microcline gneiss of the Las Brisas formation, cross joints are more common, but longitudinal or strike joints are also frequently present. The Peña de Mora gneiss, in the area around Boqueron, has cross joints which strike

schist, the joint system is quite complex and consists mainly of oblique joints.

Post-Metamorphic Structures

General statement.—The major folds and faults shown on the tectonic map of the Caracas region (Fig. 3) were formed contemporaneously with or after the metamorphism of the area. Some of these structures, particularly several of the faults, may be very recent.

The Sierra del Avila is bounded on the north and south by fault zones. It is not a simple fault block or a horst, because the faults on the

north side, the Macuto fault zone, differ in character and age from those on the south side, the Avila fault zone.

The belt of schists between the Sierra del Avila and the Caribbean coast presents a complex structure which the writer has not attempted to decipher. South and west of Caracas there are several broad folds with associated minor structures. The three principal folds are the Junquito anticline, the Cementerio syncline, and the Baruta anticline.

The north-south cross sections of Plate 1 show the major structures of the Caracas region.

Folds.—The major folds south of the Sierra del Avila are broad open symmetrical structures, with axes trending N.60°–70°E.

The Sebastopol gneiss outcrops in the center of the Baruta anticline which plunges northeast at a low angle. Toward the west it probably continues for a long distance (Aguerrevere and Zuloaga, 1937, p. 20). Near Baruta and near Sebastopol the anticlinal structure is reflected in the topography by cuestas of the microcline-mica schist. Outcrops of Zenda limestone on both limbs of the anticline substantiate the existence of this structure. Although this anticline is a rather simple structure for a metamorphic terrain, it presents more complexities than are mapped.

North of the Baruta anticline is the Cementerio syncline. The Mercedes schist lies in the trough of the syncline. Because this is an incompetent formation, it has been complexly folded and faulted on small scale. These minor structures are not shown on the map. The axis of the syncline trends about N.60°E. and plunges in the same direction. The axis is largely concealed by alluvium in the Caracas valley, but, from the outcrops of Mercedes schist east of Petare, it has been inferred that it changes trend, becoming nearly east-west and parelleling the Avila fault zone.

The Junquito anticline is another broad structure, nearly symmetrical, which parallels the Cementerio syncline on the north. Its axis plunges northeast at a low angle and is truncated by the Avila fault zone. The Antimano limestone, which outcrops on both flanks of the anticline, outlines this structure on the geologic map. The northern limb of the Junquito anticline presents several complexities, such as the smaller anticlines and synclines and minor faults in the vicinity of the Tacagua fault. These structures are probably related to movements during the faulting. North of this anticline is the Yaguara syncline.

The Sierra del Avila, as a whole, is anticlinal. However, later faulting has modified it considerably, except toward the western part, where it plunges gently in a N.75°-80°W. direction.

Faults.—Three principal types of faults occur in the Caracas region:

(1) Thrust faults dipping southward, such as the Curucutí fault.

(2) Faults striking about N.60°W. and dipping southwest, characteristic of the Avila fault zone.

(3) Faults striking almost east-west and dipping northward at high angles, typical of the Macuto fault zone.

These fault types are listed from oldest to youngest.

The Curucutí fault has been observed in the road cuts of the Old Caracas-La Guaira highway, in exposures along the railroad, and in the valley of Río Curucutí. The Curucutí serpentinite, which overlies the Peña de Mora gneiss, has been thrust over the Antimano limestone which is overturned to the north (Pl. 1, cross section B-B′). The fault plane, as exposed in a gully, strikes N.45°E. and dips 35°–40°SE. Toward the west this fault is intersected by the Las Pailas fault, and toward the east it is probably cut off by the Macuto fault zone, although the actual relationships are not evident in the field.

Other minor faults similar in dip and strike to the Curucutí have been observed, but none seems to be of major importance. Because this is the oldest type of faulting in the region, and considering that there are many younger faults, other faults of the same age and type may have been largely obliterated.

The Avila fault zone comprises several faults which bound the Sierra del Avila on the south, many of which actually cut through the flanks of the mountain. In this zone most faults strike about N.60°W. and dip 40°–60°SW. These faults, of which the Tacagua fault is the most prominent, are arranged en echelon and are bent eastward joining another fault which strikes east-west.

The Tacagua fault is nicely exposed at

Boqueron in the canyon of Quebrada Tacagua. The fault surface here strikes N.70°W. and dips 58°SW. On the north side of the fault the Peña de Mora gneiss is intensely sheared, and at the fault surface is a breccia of very fine fragments in which larger fragments are imbedded. The larger fragments are arranged in rows which rake 23°SE. Toward the west the Tacagua fault is cut off by the Las Pailas fault. Toward the east it becomes very complex in the area around Plan de Manzano, where there are numerous other faults, some paralleling it and some at high angles to it.

Another well-exposed fault surface in the valley of the Río Anauco strikes N.75°W. and dips 44°SW. Mullion structure developed on the fault surface rakes 47°SW. A thick mylonite zone forms the north side of the fault. The mylonite is fine-grained and does not present any megascopic linear structure. There are several parallel faults surfaces, all essentially with the same dip and strike, and with mylonite along them.

Farther east, a fault plane striking N.77°W. and dipping 43°SW. is intersected by another one striking east-west and dipping 70°S. On the first of these surfaces there is mullion structure with a rake of 48°SW.

The Avila fault zone presents several difficult problems. The relationships of the formations on both sides of the zone suggest these are normal faults in which the southern side has been downthrown relative to the northern side. This interpretation is also favored by the fact that the northern side is topographically higher, except for the western end of the Tacagua fault. If they are really normal faults, the explanation of a wide zone of mylonite becomes rather difficult, because commonly breccias, and not mylonites, are developed along normal faults (Anderson, 1942, p. 18). An alternative would be to consider the northwest-striking faults as having been formed as tension fractures en echelon pattern, and consider that the mylonite was formed subsequently as a result of strike-slip movements. The explanation probably has to assume two periods of movement along these faults, as will be brought out later in this discussion.

The Ocumarito fault does not form part of the Avila fault zone but seems to belong to the same type of deformation. It strikes N.65°W. and dips 65°SW. Several minor faults which are essentially parallel to it may be observed along the Río Mamo valley.

The Macuto fault zone, the youngest type of faulting developed in the Caracas region, intersects faults of the Curucutí and Avila types. This zone is characterized by northward-dipping east-west faults which are best developed on the northern slopes of the Sierra del Avila. Cortese (1901, p. 458) considered this as the most important type of faulting in the region.

Las Pailas is the most conspicuous fault of the Macuto zone. It has been traced for 20 km. and is probably longer. In the Quebrada Las Pailas, where the fault surface is poorly exposed, it dips 60°N., but, except for this exposure, the actual fault surface was not found. The fault line has been traced on the basis of lithologic and topographic evidence. At several localities there is a breccia on both sides of the fault.

In the Río Mulatos a fault surface belonging to the Macuto zone dips 56°N., and north of Maiquetía another surface, probably of the same fault, dips 60°N. There are well-developed fault breccias along both sides of these surfaces.

Stratigraphic and topographic evidence indicates that the faults of the Macuto zone are normal, with the northern side downthrown. The straightness of these faults in a horizontal direction, and their great length suggests that they have originated as strike-slip faults.

Along the coast line, or along the contact of the schists with the alluvial fans near the coast, there seems to be another east-west fault. This possible fault has not been mapped. Its existence is suggested by triangular facets which truncate topographic spurs, and by the fact that in the stream valleys smaller faults with east-west strike and high dips to the north have been observed close to the assumed position of the major fault. The author believes that this fault is like those of the Macuto zone. Kehrer (1939a, p. 699) assumes that along this same position there is an upthrust toward the north.

Kehrer made this statement in reference to one of Kamen Kaye (1938, p. 1226), who suggested that the northern flank of the Cordillera de la Costa is downdropped toward the Caribbean. The writer agrees with Kehrer that there is northward thrusting along the northern side

of the mountain, represented, however, not by the fault under discussion, but by the Curucutí fault. The thrusts are older than the Macuto zone along the Caribbean side is downthrown as suggested by Kaye.

Interpretation of the fold and fault pattern.—The major difficulties in attempting to explain the dynamics of deformation of the Caracas region are the complexities which the Avila fault zone presents. The major folds are undoubtedly older than the Avila and Macuto fault zones. Following the conventional interpretation, these folds are presumed to be the result of compressional forces acting in a north-northwest-south-southeast direction. These same forces may have formed thrust faults like the Curucutí, where the southern side was thrust over the northern side. Increase of pressure in one horizontal direction may be relieved in the horizontal direction at approximately right angles to it. This mechanism produces tension fractures arranged en echelon. The northwest-striking faults of the Avila fault zone may have originated as tension fractures. However, one fact is not consistent with this interpretation—that is, the existence of a thick mylonite zone along those faults. Tension fractures produce normal faults along which one would expect to find breccias but not mylonites. The alternative of considering these faults as the result of shearing would account for the mylonite, but the angles of dip are very low for this type of faulting. It might be better to assume, then, that they originated as tension fractures, with later shearing.

Before continuing with the explanation of the Avila fault zone, we should consider the Macuto fault zone, because the formation of this zone probably was closely related to the last movements along the already-existing fractures. The Macuto fault zone may be interpreted in two ways. It may be due to normal faulting, or it may have resulted from transcurrent or strike-slip movements. The last interpretation is favored by the fact that the zone consists of parallel faults which are long and very straight. Such features are characteristic of faults with large lateral displacement (Kennedy, 1946, p. 54–55).

Going back to the first assumption—that of compressional forces from north-northwest to south-southeast—these forces may be the compressional components of a couple acting from west to east in the northern portion of the region, and from east to west in the southern portion of the region. This effect may have produced not only the compressional and tensional components necessary for the formation of the northeast-trending folds and the northwest-striking tension fractures, but it would also account for east-west-trending shear fractures. The movements along the shear fractures is of the strike-slip type—that is, it involves a large horizontal component and would correspond to the Macuto fault zone and to the east-west fault of the Avila zone. Horizontal movements along the east-west faults must have produced similar movements along the northwest-striking fractures. During this period, characterized essentially by shearing, the mylonite along the faults of the Avila zone was probably formed. Strike-slip movements along faults which originally were formed as a result of other types of movement have been described by Anderson (1947, p. 508–513) in Scotland, in connection with the Highland Boundary Fracture zone. In fact, there is a remarkable similarity between the fault pattern of the Caracas region and some of the structures described by Anderson, although the movements have been in the opposite direction, and the fracture pattern of one is then the mirror image of the other.

The author is aware of the fact that the explanation offered to account for the structural pattern of the region is perhaps oversimplified. However, it agrees fairly well both with theory and with field relationships.

The relative movements assumed for the faults are summarized in the tectonic map of the area (Fig. 3).

Regional Deformation

General Statement

Some of the geological information obtained in the Caracas area has direct bearing on the deformational history of the southern part of the Caribbean region and may be correlated with data in other parts of the region. It is not intended to summarize here the ideas held by different authors concerning the tectonics of the Caribbean region. A good résumé of the

main trends of thought and of the outstanding features in the history of this region has been given by Maxwell (1948, p. 847–852).

The approach of Hess (1932, 1938) of explaining the deformation of the region not only on the basis of the known geological data but also on the basis of the geophysical information seems to be the most satisfactory. The following paragraphs consider some of the main conclusions reached previously by Hess as a basis for further elaboration of some concepts.

Island Arc Structure of the Eastern Caribbean Region

The main features of the development of the Caribbean island arc as a result of downbuckling of the earth's crust have been explained by Hess (1938), and further elaborated by Hess and Maxwell (1949). The crustal downbuckle has been called the tectogene. The axial region of the tectogene may have two expressions; there may be a deep-sea trough (*i.e.*, the Puerto Rico trench), or there may be a ridge either below or above sea level (*i.e.*, the Barbados ridge of which Barbados island is the part exposed above sea level). The rocks over the tectogene are highly deformed and constitute the geotectocline. The Caracas region is in the geotectoclinal zone of the Caribbean arc, and therefore the study of this region becomes rather important because it gives information on the type of structures found on that part of the arc.

At, or close to the strip of negative anomalies, intrusions of serpentinized periodotite occur (Hess, 1938, p. 84). In places two belts of serpentinites are found, one on each side of the axis of the geotectocline. Therefore, where geophysical information is lacking, it may be possible to ascertain the position of the axis entirely on geological grounds. In northern Venezuela there are two belts of serpentinites, one running from Margarita toward the west along the Cordillera de la Costa, and the other to the south along part of the Serrania del Interior. The geotectoclinal axis should lie, therefore, between these two lines of ultramafic intrusions. Hess and Maxwell (1949) consider that it runs from Higuerote to Lake Valenica, and beyond, toward Barquisimento (Fig. 1). The Caracas region lies north of the axis of the geotectocline.

The ultramafic intrusions associated with island-arc structures were emplaced when the tectogene was formed—that is, during the first great period of deformation (Hess, 1938, p. 84–85). The dating of these intrusions is important because it corresponds to the time of deformation. The age of the serpentinite intrusions in northern Venezuela cannot be determined accurately. In Margarita island they are known to be pre-Middle Eocene because sediments of this age contain chromite grains derived from the serpentinites (Hess and Maxwell, 1949). On the other hand, considering as valid the age assigned to the Los Colorados member by Dusenbury and Wolcott (1949), the serpentinites must have been emplaced after the Turonian, since in the Caracas region they intrude the Mercedes formation, of which the Los Colorados member forms the lower part.

Bucher (1947, p. 108) considers that the earliest strong period of deformation in northern Venezuela came before or during Senonian time. Senn (1940, p. 1568) favors the hypothesis of orogenesis and metamorphism at the close of the Cretaceous period. Therefore, it seems that most opinions favor a great period of deformation during the late Cretaceous. Two essentially different opinions have been expressed, however. González de Juana, in his discussion of the diastrophic history of northeastern Venezuela (1947), considers the metamorphic rocks of the Paria-Araya region as being unconformably below the unmetamorphosed Barranquín (Early Cretaceous) formation and concludes that the main period of orogenesis was pre-Cretaceous. Recently Dusenbury and Wolcott (1949) expressed the opinion that the metamorphism occurred during either Paleocene or Eocene.

After the intrusion of the ultramafics the geotectocline was farther deformed, and probably at this time most of the regional metamorphism took place, affecting also the ultramafics. The isogeotherms in the tectogene were raised (Kennedy and Anderson, 1938, p. 72), causing remelting of the crust and injection of igneous material into the upper layers, the geotectocline, producing migmatite zones

(Umbgrove, 1947, p. 72, 186), and *lit-par-lit* injection gneisses (*i.e.*, Peña de Mora gneiss).

Thrusting outward from the axis of the geotectocline followed the metamorphism, as evidenced by the Curucutí fault, on the north side of the axis. Extensive thrusting toward the south is known to have occurred along the southern border of the Serranía del Interior, on the south side of the axis.

Later deformation was characterized by the development of the east-west fractures along which movements with a large horizontal component took place, such as the Avila and Macuto fault zones, in which it has been postulated that the northern side moved eastward. This type of deformation may perhaps be correlated with similar structures in other parts of the Caribbean region. Los Bajos fault in Trinidad (Wilson, 1940) is a large strike-slip fault along which the northern side has also moved relatively eastward. In the northern portion of the Caribbean region, the Bartlett trough south of Cuba, and the Anegada trough south of Puerto Rico have been interpreted as large transcurrent faults (Hess, 1938, p. 87), along which the south side moved eastward. If the interpretations of those structures on both the northern and the southern portions of the Caribbean region are correct, it may be postulated that the central portion of the region has moved eastward, which is consistent with the type of movement necessary to explain the formation of the Lesser Antilles arc. Of course, much more information is needed, particularly in northern Venezuela, before the preceding statement can be fully supported.

While a region is subject to the type of stresses which must be involved during the formation of a crustal downbuckle, no matter what the origin of the stresses, the region is under a condition of dynamic equilibrium. After the stresses are released the region will adjust itself to a condition of static equilibrium (isostasy), during which the expected result would be the uplift of the geotectoclinal zone. Such movements may explain the rapid uplift of the Caracas region in Tertiary and Recent times. With the information now available it is not possible to date the beginning of the uplift. Miocene sediments in Cabo Blanco and Oligo-Miocene sediments in the Tuy Basin, made up of materials derived from the metamorphics, indicate that uplift preceded their deposition. However, the uplift may have started long before Oligocene. Senn (1940, p. 1589) suggested that the emergence of the Cordillera de la Costa began in Late Eocene. According to Manger (1932), the main uplift in northeastern Venezuela occurred during or after Pliocene. In the Caracas region it is certain that the uplift during the Pleistocene and Recent epochs has been considerable.

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GEOLOGY OF THE LOS TEQUES–CUA REGION, VENEZUELA

By Raymond J. Smith

Abstract

The Los Teques-Cua portion of the Coast Range of north-central Venezuela consists essentially of a granitic basement overlain by two metasedimentary and metaigneous complexes of probable Cretaceous age, locally covered by unmetamorphosed volcanic and Tertiary sedimentary rocks.

The Sebastopol orthogneiss forms the basement, overlain unconformably by the Caracas metasedimentary series. Although now gneissic, the Sebastopol was probably unmetamorphosed, coarse-grained granite when the sediments of the Caracas series were deposited.

The Older Metamorphic Complex, the Caracas series, is chiefly metamorphosed sediments seemingly deposited on a stable platform in a transgressing early Cretaceous sea. This sequence of arkoses, conglomerates, orthoquartzites, dolomitic and reef limestones, and calcareous and noncalcareous shales was metamorphosed to microcline dolomite rocks, and schists and marbles of the Las Brisas formation, the Antimano limestone, and the Las Mercedes formation. An amphibolite layer, possibly representing a metamorphosed basaltic flow, occurs interbedded in the sequence. Well-defined schistosity and lineation were developed during the folding and metamorphism.

The sediments of the Younger Metamorphic Complex, the Paracotos formation, lie unconformably above the Older Complex and represent rapid deposition under eugeosynclinal conditions. They consist of a mixture of graywackes, conglomerates, and cherts, interbedded with tuffaceous and limy layers. Most of the clastic material for the graywackes was derived from the already exposed Caracas series schists and the Sebastopol basement. The Paracotos sediments were intruded by peridotitic igneous rocks and a hornblende diorite with related dikes of soda granite. Metamorphism of this complex to the muscovite-chlorite subfacies of the green-schist facies shortly after the emplacement of the igneous rocks converted the sediments to phyllites and metagraywackes and imparted a slight schistosity and microfold lineation to all the rocks affected. The ultramafic intrusives were also partly altered to antigorite in the northern outcrops. In neither this nor the earlier metamorphism of the Caracas series was a thick cover of sediments present.

The Tiara volcanics consist of gabbroic dikes and sills and basaltic flows emplaced immediately after the metamorphism of the Younger Complex. These, together with the earlier metamorphics, were being eroded by Coniacian time, supplying material to the Late Cretaceous, Tertiary, and Quaternary sediments.

Structurally the region lies on the southern limb of the major anticline which trends N.75°E. across the northern part of the area. All magnitudes of folding occur in these rocks, from the large isoclinal folds to the microscopic fold lineation. Faulting is also prominent chiefly as N.80°E. transcurrent faults and their accompanying N.60°W. normal faults. Thrust faults, probably older than the transcurrent faults, occur locally.

The region is rugged. Youthful streams are cutting rapidly into an uplifted erosion surface.

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Introduction

Physical Geography

Along the northern coast of Venezuela a nearly continuous east-west trending belt of mountains separates the llanos from the Caribbean Sea. This range extends from Barquisimeto in the west to the Paria Peninsula in the east, and continues eastward as the North Range of Trinidad. The portion of these ranges studied in this paper is between latitudes N.10°10′ and N.10°25′, and longitudes W.66°50′ to W.67°10′ (Fig. 1); it is a rectangle of 1215 square km. roughly delimited by the towns of Los Teques, Las Tejerias, Charallave, and Cua.

Elevations range from 200 m. in the Tuy Valley to 2000 m. in the northwestern sector; a local relief of 1000 m. is not unusual. The relatively high overall elevation, combined with a 35-inch rainfall, results in a pleasant climate for the abundant village and farm population. The 475 square km. of Tuy Valley comprises the only low-level area of slight relief in the region and acts as a temporary base level for the Tuy River.

The physiographic characteristics of the Los Teques area are typical of the Coast Range, as all of it has been subjected to essentially the same geologic history. Of primary importance is a widespread Tertiary erosion surface (Aguerrevere and Zuloaga, 1937, p. 10), seen today as extensive highland areas of low relief and ridge tops traversing great distances with little change in elevation. This surface presumably was uplifted in Tertiary time; the action was intermittent and accomplished chiefly by faulting. The amount of vertical movement decreases irregularly toward the south; thus the larger remnants are in the more highly elevated region around Los Teques and Carrizal. The youthful streams and the rugged relief suggest relatively rapid movement. As noted by Aguerrevere and Zuloaga (1937, p. 10), a second surface at a lower elevation was developed during Pleistocene time in the Tuy Valley and is now being entrenched.

The drainage of much of this region has a distinctive rectilinear pattern (Fig. 2), the result of numerous, almost parallel, transcurrent faults crossing the area; the accompanying crush zones controlled subsequent erosion. In areas of great uplift, as in the northern part of the region, many of the larger streams follow these faults in deep gorges. Numerous incised meanders were also noted; their pattern developed by superimposition. Many examples of antecedent streams also exist. Most of the smaller streams in the area are still in a youthful insequent stage.

Previous Work

The early geologic work done in this part of northern Venezuela has been summarized by Dengo (1953, p. 8). Early workers in the region included Humboldt (1804), Karsten (1850–1851), Wall (1860), and Sievers (1887); and more recently Lamare (1927), Schuchert (1935), Kehrer (1937), and Liddle (1946). Studies concerning the general regional relationships have been made by Hess and Maxwell (1949), Bucher (1949), and Mencher (1951). Unpublished investigations of the Tertiary sediments have been carried out by various petroleum companies.

In the initial study of the metamorphic rocks, Aguerrevere and Zuloaga (1937) recognized the sequence of the various rock types, divided the section into units, and drew a broad picture of the regional history. Their work has proved correct in most respects. Dengo did the first detailed investigation of the metamorphics in the vicinity of Caracas. Most of the lithologic divisions and structural ideas developed in his work also apply to the Los Teques area.

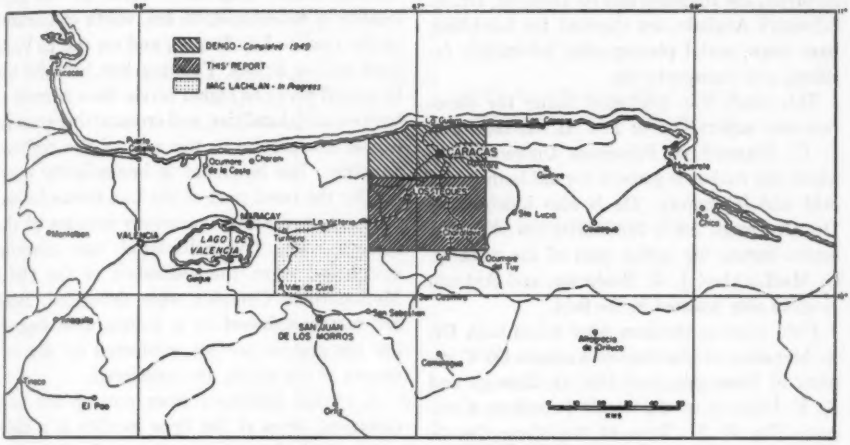

FIGURE 1.—LOCATION OF THE LOS TEQUES-CUA REGION

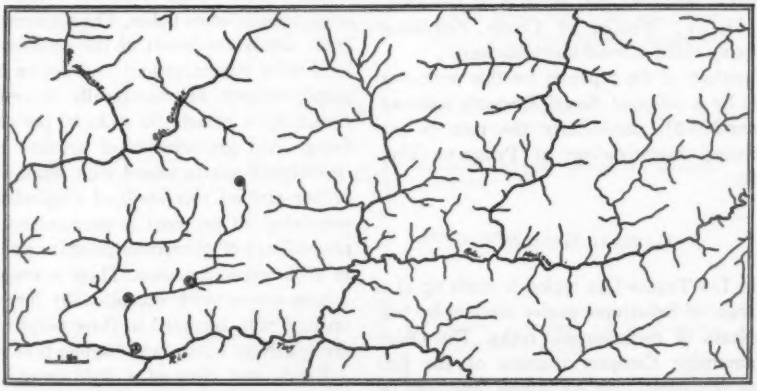

FIGURE 2.—RECTANGULAR STREAM PATTERN IN THE WEST-CENTRAL PART OF THE AREA

Acknowledgments

The field work for this report was carried on between June and October 1949, and July and

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This study was conducted under the direction and supervision of Drs. H. H. Hess and J. C. Maxwell of Princeton University, to whom the author is grateful for aid both in the field and laboratory. He is also indebted to Dr. G. Dengo for a familiarization with the region during the earlier part of the work. J. C. MacLachlan, J. R. Bushman, and Antonio Nogales ably assisted in the field.

Field trips to the area were taken with Dr. E. Mencher, of the Socony Vacuum Oil Company of Venezuela, and Drs. G. Zuloaga and K. F. Dallmus of the Creole Petroleum Company. Dr. H. H. Renz of the Mene Grande Petroleum Company, Dr. S. de Civrieux of the Instituto Nacional de Minería y Geología, and Dr. V. Winkler of Creole Petroleum Company aided in fossil identifications.

A portion of the expenses for this work was borne by a Office of Naval Research contract (N6onr-27008), particularly the cost of the laboratory investigations at Princeton University.

General Geology

The Los Teques-Cua region is made up of a basement of Sebastopol gneiss overlain by two complexes of metamorphic rocks. The Older Metamorphic Complex consists of the Las Brisas formation, the Antimano limestone, a layer of amphibolite, and the Las Mercedes formation. In the past the name "Caracas series" has been applied to the metasediments of the Older Complex, and in this report the two terms are used interchangeably. The Younger Metamorphic Complex consists of the Paracotos formation and intrusions of hornblende diorite, soda granite, and ultramafic rocks. The Tiara volcanics were emplaced subsequent to the metamorphism, and Tertiary and Quaternary sediments were locally deposited. Figure 3 shows the columnar section.

Basement

The granitic Sebastopol orthogneiss underlies unconformably the metasediments of the Caracas series. Exposures occur at the type locality of Sebastopol, 26 km. south of Caracas on the road to Los Teques, and on the El Valle road at Las Brisas. Faulting has brought the basement rocks to higher levels than normal at both outcrop localities, and crosscutting streams expose the granite in the core of the regional anticline. The basement is immediately overlain by the basal part of the Las Brisas formation, which contains numerous pebbles of the igneous rock. The Sebastopol was unmetamorphosed when the sediments of the Older Metamorphic Complex were deposited. Both are metamorphosed to a comparable degree, but the granite pebbles, protected by the soft matrix of the schist, are unsheared.

A typical specimen from one of the less-deformed zones at the type locality is a pale-green, little-deformed, coarse-grained igneous rock, with a rough foliation suggested by orientation of mica flakes. The apparent coarse grain size is the result of the combination of local mica concentrations and coarse feldspar porphyroblasts. Microscopically, however, it is essentially a cataclastic rock; 80 per cent is a fine-grained groundmass of crushed and recrystallized quartz mixed with small amounts of fine-grained recrystallized plagioclase. The remaining 20 per cent is predominantly porphyroblasts of microcline perthite and albite in about equal amounts. These average about 2 mm. across, with exceptionally large grains up to 4 mm. Included in these porphyroblasts are relatively unstrained fragments of quartz.

Bands and clots of a light-green, slightly pleochroic mica are found in the groundmass. $N_y = 1.601$, and $2V\ (-) = 38.5°$. Accessory minerals include fairly large amounts of magnetite associated with the mica; epidote occurring along fractures and in altered feldspars; and smaller amounts of pyrite, biotite, apatite, garnet, and zircon. Chlorite occurs in numerous veins.

The feldspars in this rock may be observed in varying stages of alteration to sericite and kaolinite.

Much straining and fracturing of the grains has occurred subsequent to recrystallizatio

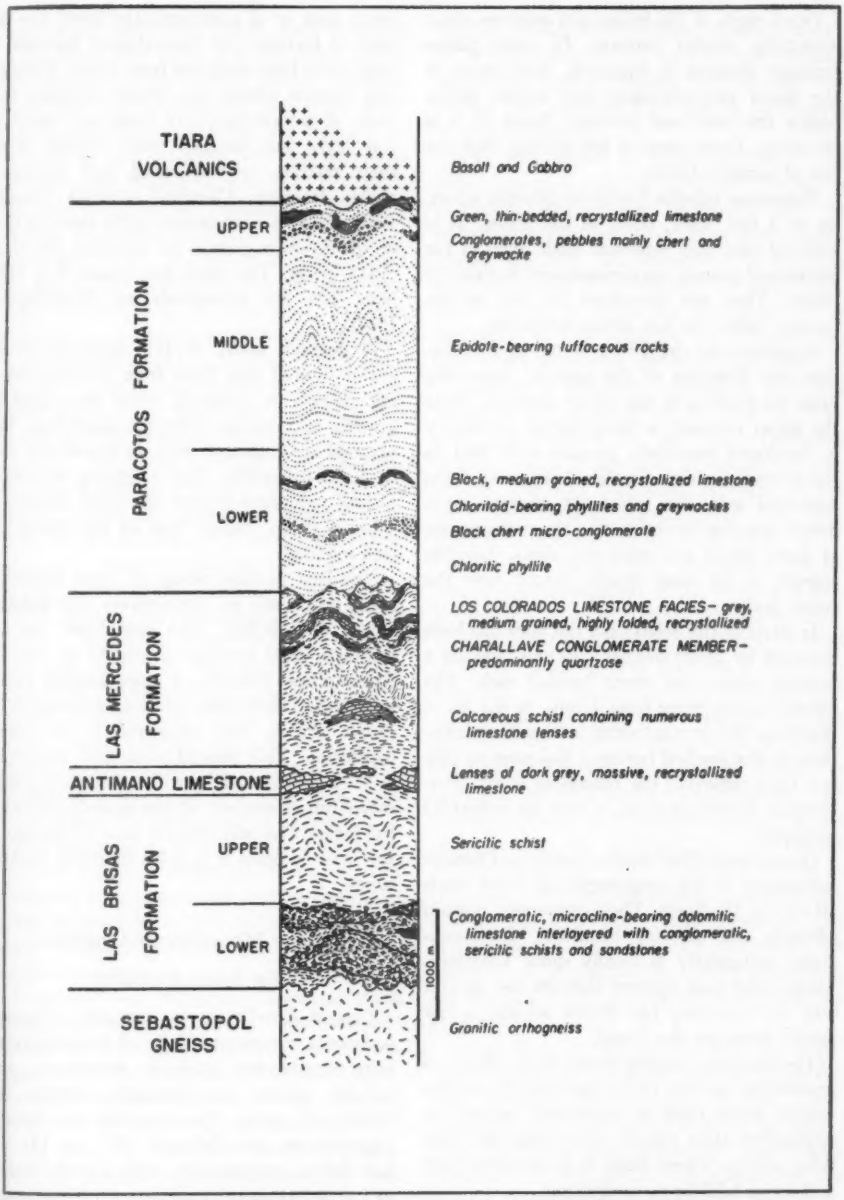


FIGURE 3.—COLUMNAR SECTION IN THE LOS TEQUES-CUA REGION

probably related to the younger faulting in the region. The major effect appears to have been on the quartz, although some of the plagioclase lamellae are bent. A mortar structure on the borders of the coarser grains is produced where crushing has occurred.

Other parts of the Sebastopol outcrops show essentially similar features. In some places stronger shearing is indicated, with many of the larger porphyroblasts and quartz grains highly fractured and strained. Some of it is mylonitic. Local areas of fine-grained rock are free of porphyroblasts.

Numerous veinlike bodies of chloritic schist, up to 2 feet thick, occur in the gneiss. It is believed that they represent basic dikes in the Sebastopol granite, metamorphosed to chloritic schist. They are truncated by the unconformity below the Las Brisas formation.

A pronounced change was noted in the foliation and lineation of the granite, depending upon its position in the major anticline. Near the upper contract, a fairly strong schistosity is developed essentially parallel with that in the overlying schists. Farther down, toward the anticlinal axis, the schistosity changes to a pencil lineation resulting from the stringing out of flaser zones and mica-rich areas. Jointing appears to be more closely spaced near the larger faults.

In parts of the Sebastopol the mica has been removed by hydrothermal solutions, leaving a massive white and green banded rock. The colored layers range from 1 mm. to 0.5 m. in thickness. Where weathering is deep, the plagioclase in the leached horizons has gone to clay and been removed; the remaining quartz concentrate, a white powder, is used for industrial purposes.

Quartz veins filled tension cracks and fissures subsequent to the metamorphism; some reach 50 cm. in thickness. They commonly contain adularia and specular hematite; the specularite particularly is locally quite abundant. These veins pass upward through the contact into the overlying Las Brisas schists. A few calcite veins are also found.

The basement granite shows fairly advanced weathering in most of its outcrops. Its characteristic white color is sometimes masked by ferruginous stain washed down from the overlying schists. Where fresh, it is relatively hard and forms boulder-covered slopes.

Because the Sebastopol gneiss is mineralogically like layers in the overlying Las Brisas schists, there is a question whether this rock was formed from the metamorphism of an igneous rock or of a sedimentary layer. On the basis of textural and mineralogical features, it could have been produced from either. Coloring and textural effects that closely simulate features of metasedimentary rocks are found in this body, but detailed study clearly shows their relation to weathering and joint-controlled leaching. Chemical analysis (Dengo, 1953) shows a composition fairly close to that of the average granite as compiled by Daly (1933, p. 9). The silica percentage is a little high, but not excessively so (Washington, 1917).

A detailed study of the accessory zircon grains showed that those from the Sebastopol are pinkish to purplish, often show parallel growth, and contain numerous inclusions. The crystals are euhedral, with no observable evidence of corrasion. The overlying metamorphosed sediments contain the same distinctive type of zircon, except that all the grains are well rounded.

The first detailed study of these basement rocks was made by Aguerrevere and Zuloaga (1938, p. 259–260), who considered the Sebastopol basal complex a granite of possible Archean age. Recently, a more detailed petrographic and chemical study was undertaken by Dengo (1953), who concurred in the above conclusion. This present work also attributes to it an igneous origin, with subsequent metamorphism equivalent to the epidote-amphibolite facies. The only definite data on the age of the mass indicate it is older than the Caracas series.

Older Metamorphic Complex

Las Brisas Formation

General description.—A sequence of metasediments composed chiefly of conglomerates, microcline-bearing gneisses, limestones, and sericitic schists unconformably overlies the Sebastopol gneiss. This sequence was named (Aguerrevere and Zuloaga, 1937, p. 13) the Las Brisas conglomerate, with a type locality at Las Brisas on the road between Caracas and Charallave. Aguerrevere and Zuloaga assigned a thickness of 500 meters to the lower conglomerate and a like thickness to the overlying calcareous "Zenda phase". The schist layers

immediately above the Zenda were classified as the lower part of the Las Mercedes formation. Detailed work on the section, however, makes desirable a change in their subdivision. The conglomerate layers are not confined to their lower, conglomeratic part, but are more abundant near the top of their "Zenda phase". The lower rocks are predominantly schists and gneisses containing porphyroblastic, and not clastic, microcline. In view of this, the writer has revised the Las Brisas into an upper and lower member (Fig. 3). The lower member distinctively contains conglomerate pebbles, microcline porphyroblasts, and carbonate beds. The upper Las Brisas consists of the schistose layers between the uppermost microcline-rich horizon and the overlying Antimano formation.

Lower Las Brisas.—Quartzose sericitic schists, ranging in thickness up to 250 m., directly overlie the Sebastopol gneiss and in many places interfinger with limey, microcline-rich layers. These fine-grained rocks generally are light gray, weather greenish, and are chiefly sericite, quartz, and plagioclase in varying proportions. Associated heavy minerals include magnetite, light- to dark-brown pleochroic tourmaline, rutile, leucoxene, garnet, staurolite, and well-rounded pink zircons. Local areas are rich in calcite, together with numerous quartz veins crosscutting the well-developed schistosity. Quartz-hematite-adularia veins like those in the Sebastopol gneiss are also present.

The basal quartz-sericite schist grades upward into a slightly calcareous, quartzose schist containing a few microcline porphyroblasts. It is well foliated, with mica-rich and mica-poor bands. Occasional stretched quartz pebbles are found in this zone.

A gneissic rock containing abundant black microcline porphyroblasts in a recrystallized calcareous groundmass occurs above and interfingers with the previously described layers. The porphyroblasts make up only about 5 per cent of the rock and may be as large as 1 cm. in diameter. Some have exsolved plagioclase to produce microcline perthite, and quartz grains are found scattered in them. The gray matrix consists of two-thirds recrystallized calcite and one-third recrystallized quartz, with a few grains of oligoclase. Areas in the matrix of local quartz concentration are probably crushed pebbles. Sericitic mica occurs in layers; its orientation gives the rock a good foliation. Magnetite, pyrite, ilmenite, clinozoisite, leucoxene, and rounded pink zircons are present in minor amounts.

This rock is not so highly sheared as the Sebastopol gneiss, probably because the matrix is plastic. Neither the plagioclase nor the microcline shows any evidence of post-crystallization shearing. The formation is structurally competent, and it is resistant to weathering; the only effects noted are the alteration of microcline to clay minerals. As a result, this rock forms prominent cuestalike outcrops.

Table 1, a chemical analysis of a typical sample of microcline gneiss from the La Mariposa quarry, shows that the rock is composed of about equal proportions of silicate and carbonate. The high percentage of MgO, with a CaO:MgO ratio of approximately 1:1, indicates the carbonate mineral is dolomite.

Seemingly considerable movement accompanied the development of the microcline porphyroblasts, as most of them are well rounded. Their porphyroblastic origin is clearly attested to by the usual growth features, a relatively large size, and the lack of a metamorphic texture. According to Turner (1948, p. 84), the ratio $CaO+K_2O+Na_2O/Al_2O_3$ must be greater than unity if potash feldspar is to develop in preference to mica during metamorphism. The chemical analysis corroborates his belief, as the ratio for this rock is about 3:5. The largest porphyroblasts are found in rocks very rich in carbonate; the carbonate-poor ones generally contain plagioclase rather than microcline. The abundance of CaO in this rock relative to the quantity of plagioclase has locally resulted in the formation of clinozoisite along with the plagioclase.

About 70 m. of this massive gray rock is exposed at the La Mariposa quarry, where the beds average approximately 30 cm. thick. Some, however, are as much as 15 m. thick. This particular microcline-rich zone thins westward and has almost disappeared on the western border of the mapped area. The thick-bedded portions, characterized by a rectangular joint pattern, furnish ideal building stone.

Thinner beds, composed almost completely of limestone, are associated with the microcline

gneiss. These are dark gray, medium-grained, and massive except for local schistose partings. The dark-gray color is believed to be caused by graphite. A few grains of quartz, microcline, and plagioclase are also commonly included.

TABLE 1.—CHEMICAL ANALYSIS OF THE MICROCLINE GNEISS, DF232

James J. Engel, Analyst, Rock Analysis Laboratory, University of Minnesota

SiO_2	43.98
Al_2O_3	5.31
Fe_2O_3	.15
FeO	.22
MgO	10.05
CaO	14.39
Na_2O	.98
K_2O	2.51
H_2O^+	00
H_2O^-	.02
CO_2	22.28
TiO_2	.07
P_2O_5	.06
MnO	.04
Total	100.06

Younger calcite veins cut this rock, but no quartz veins occur in either this or the underlying microcline horizon.

The microcline-rich rocks grade upward into a 400-meter thick layer of mica schist. As is shown in the columnar section, the beds here become markedly conglomeratic. The layers below contain pebbles, and some are fairly large, but they are relatively rare. The schist matrix of this conglomerate is gray, strongly lineated, and not highly contorted. A few areas locally rich in microcline porphyroblasts are found, as well as graphitic layers up to 4 feet thick. The pebbles are predominantly quartz and granite, with an observed maximum diameter of 8 inches. The degree of rounding varies considerably, but none are highly angular. Most have been flattened or elongated during metamorphism.

Light and dark quartz pebbles are numerous; most of them have been strongly sheared and crushed; however, their pre-metamorphic rounded shape is still recognizable. Of greater importance are the medium- and coarse-grained granitic pebbles probably derived from the Sebastopol basal complex. These commonly consist of quartz, microcline, and a little plagioclase, plus coarse white or green mica. In some cases, the potash feldspar is orthoclase rather than microcline, suggesting that locally the shaley matrix had a sufficient cushioning effect on the conglomerate fragments to prevent the metamorphism from bringing about the change. In addition, little evidence of shearing is found in them. They have a poorly developed foliation and lineation. Heavy minerals include ilmenite and leucoxene, together with euhedral pink zircons.

The conglomerate-bearing schist grades upward through several light-colored limestone layers into the second major microcline-rich zone, described by Aguerrevere and Zuloaga (1938, p. 259) as the "Zenda phase". This consists of about 75 m. of gray, medium- to coarse-grained microcline gneiss interbedded with massive, gray limestone layers. The microcline porphyroblasts in this rock range up to 6 mm. in diameter. An appreciable amount of quartz, some as pebbles, is also found. The specularite-quartz veins, common in the lower rocks, occur sparingly here. Considerable lateral variation was noted both in the thickness and composition of this microcline-rich horizon.

Dengo suggests that the El Encantado limestone outcrops are equivalent to the Zenda member (1953), but the evidence from this present work indicates that this is unlikely. The El Encántado material differs in both composition and appearance from the Zenda; it is more similar to the numerous lenticular bodies higher in the section. The Zenda and its associated microcline gneisses are traceable across the entire area with no rapid changes in features, and it is therefore unlikely that the brecciated limestone of El Encantado near-by is part of the same body.

Above these massive, microcline-bearing limestone layers, the rocks are predominantly schists, with thin layers of hard microcline rocks. The contact between the lower and upper parts of the Las Brisas formation is gradational; the number of conglomerate pebbles and microcline layers of the lower Las Brisas decreases until the rock becomes the sericitic schist of the upper Las Brisas.

FIGURE 1. COARSER FACIES OF THE LAS BRISAS CONGLOMERATE
Lower pebble is granitic. Photography by G. Zuloaga.

FIGURE 2. SMALL-SCALE FOLDING AND SHEARING TYPICAL OF THE PARACOTOS FORMATION
Plane light, 20X.

FEATURES OF THE METASEDIMENTARY ROCKS

Upper Las Brisas.—The series of folded sericitic schists (average thickness 1000 m.) making up the upper part of the Las Brisas formation overlies and is intercalated with the microcline porphyroblastic and conglomeratic layers. Its usual gray or brown color is masked in places where graphite flakes coat the sericite. Accessory minerals include light-brown tourmaline, magnetite, epidote, rutile, and a few rounded zircons.

In places hard layers are found, composed almost completely of fine-grained recrystallized quartz. This rock usually is white or gray, in some places stained by limonite. Chlorite has locally been developed in these layers, particularly near faults.

Dark graphitic-clayey layers are numerous in the uppermost part of this sericitic series. They average about 5 cm. thick, although some attain a conspicuous 1½ m.

Quartz veins are rare, particularly high in the section. Almost invariably they parallel schistosity. Post-metamorphic quartz veins, probably formed from the same solutions that deposited the specularite and adularia veins in the underlying Sebastopol basement, are also found. No specularite is found this high in the section, but large muscovite and garnet crystals are common.

Except where highly faulted, the small-scale folding in these rocks is not so intense as in the overlying Las Mercedes formation. Almost no small-scale folding is found in its lower part, the beds probably were protected by the massive calcareous layers below. Pronounced schistosity and microfold lineation are developed throughout.

Although a siliceous layer may form a prominent outcrop, most of this sericitic schist is deeply weathered and forms gentle slopes and rounded hills. The yellow clay produced is characteristic of the Las Brisas schists.

Antimano Limestone

Although in places the calcareous Las Mercedes schist is in contact with the upper part of the Las Brisas formation, lenticular masses of dark-gray limestone usually occur at the contact. These massive limestones, separating a calcareous from a noncalcareous schist, have been named the Antimano limestone. Their type locality is at Antimano in the vicinity of Caracas (Dengo, 1953, p. 15). The lenticularity suggests that not all the outcrops are contemporaneous. Nevertheless, the lowest massive limestone zones mapped in the lower Las Mercedes formation are regarded as the Antimano limestone.

This rock usually is dark gray, with local areas of fine-grained graphite concentration. A few small detrital quartz grains are present, as well as pyrite metacrysts. Chemical analyses of Antimano samples show only a small amount of magnesium. The grain size varies considerably; most of the crystals are less than 1 mm. in diameter. Recrystallization of the calcite has resulted in a preferred orientation of the grains; the rock apparently has been little affected by later crushing. Quartz-ankerite lenses, calcite veinlets, and crosscutting quartz veins are abundant. Calcite crystals coat many of the joint surfaces. Thin layers of seritic schist commonly separate the more massive limestone beds.

The maximum observed thickness of the lenticular bodies in the Los Teques-Cua region is 300 m. This limestone, more resistant to weathering and erosion than the surrounding schists in most localities, forms cliffs and ridge cappings.

Amphibolite

A 2-meter layer of epidote amphibilite occurs in the Las Mercedes schist close to the Antimano limestone contact. This occurrence south of San Pedro was first described by Lamare (1927, p. 143) and is unique in this area.

The rock is typically dark green, medium-grained, equigranular, and massive. About 40 per cent of it is composed of a pleochroic hornblende, with X = yellowish green, Y = light green, and Z = dark green, 2V (−) = 77°, and Z Λ c = 20°. Another 40 per cent consists of coarse-grained epidote, 15 per cent is somewhat altered albite, and 5 per cent is quartz. There are also accessory pyrite, sphene, and apatite. A crystalloblastic texture has resulted from the growth of both the hornblende and epidote. The quartz appears to have crystallized later and fills the interstices.

This rock is similar to Dengo's specimen DF296, obtained from outcrops near Anti-

mano. Both occur at about the same horizon, are concordant, and are associated with the near-by massive Antimano limestone beds. The rocks from Antimano, however, contain glaucophane and are much more strongly sheared; the grains show a well-developed preferred orientation.

Las Mercedes Formation

General description.—A complexly folded series of calcareous schists conformably overlies the lenticular Antimano limestone and the Las Brisas formation. Aguerrevere and Zuloaga (1937, p. 14–16) named them the Las Mercedes schists, from the type locality at Las Mercedes.

In the present study, the Las Mercedes formation is subdivided into the Las Mercedes schist proper, the Charallave conglomerate member, and the Los Colorados limestone facies. Intense isoclinal folding and the fact that the upper contact is consistently a fault make it impossible to give a precise thickness to the formation, but 1600 m. is a minimum.

Las Mercedes schist.—The schist of the Las Mercedes formation is similar to that described in the upper part of the Las Brisas formation, but much more calcareous. Gray to brown when fresh, it weathers to a typical pink clay. It is composed predominantly of medium-grained recrystallized calcite, intermixed with fine-grained sericite. Fragments of quartz are observed, often as fine grains concentrated in a small area, possibly representing highly crushed quartz pebbles. This quartz is locally sufficiently concentrated to be recognizable as layers in the calcareous matrix. Graphite is abundant in the lower part of the section; a relatively small amount gives the schist a black color. One graphite-rich bed, having commercial possibilities, is 7 m. thick.

The intercalated layers of noncalcareous schist are usually massive, light brown, and composed chiefly of crushed quartz and sericite. Small grains of uncrushed quartz and recrystallized plagioclase are present, and chloritoid is sparingly found.

Most of these rocks have well-developed, closely spaced schistosity planes, produced by orientation of the sericite and elongation of the calcite grains. Most of them also have a good microfold lineation. All show a high degree of contortion, evidence of an extremely incompetent rock type. Secondary shear planes are quite common, probably the result of later fault movements.

The calcareous schist has been mylonitized in and near the large transcurrent faults of the region, resulting in a very resistant rock composed of crushed quartz, muscovite, and graphite, in a calcareous matrix. It is commonly colored green by the development of chlorite. Crushing has been so intense in places that no individual grains can be distinguished.

Quartz veins are more abundant in the upper part of the Las Mercedes formation than in any other part of the Caracas series. They are usually highly contorted lenses up to 10 cm. thick and develop parallel to the schistosity or along joints. Calcite and ankerite veins are associated with some of the quartz veins.

Tertiary or Quaternary weathering in these calcareous schists has locally produced a conglomerate of metamorphic fragments in a matrix of brown limestone. Caliche also mantles many of the Las Mercedes hills in the western part of the area.

Charallave conglomerate member.—Aguerrevere and Zuloaga (1937, p. 17) described the Charallave conglomerate as the basal conglomerate of the younger Villa de Cura series, with a type locality on the road between El Valle and Charallave. In this paper the Charallave conglomerate is placed within the upper part of the Las Mercedes formation. Its position is definitely established, as it crops out about 15 m. below the Los Colorados limestone at its type locality near Los Colorados.

It is typically a massive gray rock composed of rounded quartz pebbles set in a fine-grained matrix consisting predominantly of highly crushed quartz, some of which may be recrystallized chert. When slightly weathered some of the rock has a pronounced reddish tinge produced by hematite staining. The larger quartz grains, up to 20 mm. in diameter, appear to have been partially recrystallized and later shearing has given them an undulatory extinction. Many grains are black, probably due to graphite flakes along grain boundaries. This rock shows little evidence of schistosity or lineation.

A facies of the conglomerate containing much fine-grained quartz is associated with sericitic

schist. It shows gradational relationships with the schist, and schistosity and lineation develop with increasing sericite content. Magnetite, biotite, and blue tourmaline are accessory minerals. This facies is intimately associated with limestone in parts of the area; the intermixture produces a fine-grained calcareous sandstone.

The Charallave conglomerate usually crops out as small lenses which occupy roughly the same stratigraphic position throughout the area mapped. These lenses are seldom more than 4 m. thick, and most of them are less than 20 cm. Stringers of black recrystallized limestone accompany most of the lenses. Where composed of essentially pure quartz, the conglomerate forms an extremely resistant rock, resulting in boulder-covered slopes. Where a small amount of schist is included, however, the conglomerate weathers comparatively readily to a fine rubble.

This rock is highly crushed and sheared near faults; some of it is mylonitized. Locally it appears to have been later hydrothermally altered, with cracks and shear surfaces covered by coarse mica and hematite.

Los Colorados limestone facies.—Aguerrevere and Zuloaga (1937, p. 16) named the numerous limestone lenses in the Las Mercedes schist the Los Colorados limestone, with a type locality at Los Colorados on the road between Los Teques and Las Tejerias. While they considered this as a more or less continuous layer over much of the area, detailed field work has shown that probably no bed extends any great distance. For that reason, the writer prefers to use this term as a facies designation covering all of the thick-bedded lenticular limestone layers in the Las Mercedes schist, regardless of the level at which they occur. Most of these Los Colorados type lenticules occur fairly close to the top of the exposed Las Mercedes formation, as is indicated in the columnar section.

All these highly folded limestone lenses are similar in that they are uniform in texture, gray to black, commonly intercalated with layers of calcareous schist, and range from thin-bedded schistose to thick and massive. They consist almost completely of recrystallized calcite, with less than 1 per cent detrital quartz. In some places they are strongly stained by limonite or hematite, and they may be gray or black from included graphite. Folding is usually quite intense in these rocks; the fold axes trend roughly parallel to the strike of the major regional anticline. Where they are interlayered with schist, a good lineation is developed on the sericitic layers.

Some of this rock shows brecciation and crushing similar to that in the El Encantado limestone. Crosscutting quartz veins are locally numerous, as are ankerite-calcite veins. Many of the joint surfaces are coated with calcite crystals.

Deposition and Metamorphism of the Older Complex

The sediments constituting the Older Metamorphic Complex were probably deposited under conditions simulating quite closely a normal stable platform type of accumulation (Pettijohn, 1949, p. 451–460). The sequence began with the arkosic sedimentation of the lower part of the Las Brisas formation. These rocks, now observed as the layers of conglomeratic, microcline-bearing schist, possibly represent a nonmarine phase, but there is little positive evidence for this assumption. As has been noted in many other areas of similar transgressive relationships, a thin zone of shaley material locally separates the basement granite from the first arkosic clastics. The arkose zone in this region contains numerous orthoquartzite and arenaceous limestone layers, some of which locally rest on the basement. These increased in abundance as deposition continued, until the sequence graded upward into the thick zones of dolomitic microcline gneisses representing the orthoquartzite-limestone facies. The true orthoquartzite beds in this part of the sequence are thin, the abundant microcline porphyroblasts indicate continued pulses of arkosic sedimentation. In this particular area, it would possibly be better to consider this a period of feldspathic sandstone deposition, rather than true orthoquartzite. Most of the thin, irregular conglomeratic zones also occur in this portion, rather than lower, suggesting a possible near-shore environment. Continued sinking of this stable area resulted in a gradual increase in shale deposition, with the formation of the relatively pure shale

zone of the upper part of the Las Brisas formation. Deposition of autochthonous limestone soon followed in the limestone lenses, probably biohermal, of the Antimano. About this time, basalts now seen as the epidote amphibolite were extruded. The sedimentation above the Antimano limestone was much more calcareous and represents the marly deposition of the bathyl, limestone-shale facies of the sequence. Reefs were numerous at this time and constituted the thick zones of massive limestone of the Los Colorados facies. Some of the layers of thinner, more well-bedded, calcareous rock were possibly of biostromal origin. The quartzose Charallave conglomerate is locally interbedded with these limestones and does not fit into the pattern of the typical foreland facies. It is believed to represent the first sign of orogenic activity, with perhaps a slight uplift of a low-lying, deeply weathered source area from which the residual quartz rubble was stripped by erosion.

The above series of sediments was subjected to a medium grade of metamorphism subsequent to their deposition; the shales altered to schists, the limestones to marbles, and the calcareous and arenaceous lower layers to microcline gneiss. That the sequence fits into the epidote-amphibolite facies is shown by the development of albite, epidote, and amphibole in the metabasalts associated with the Antimano limestone. It is also suggested by the assemblage: quartz, microcline, albite, epidote, typically found in the schists.

Well-developed foliation and microfold lineation are found in all these rocks. The foliation has been produced primarily by parallel growth of sericite, while the lineation results from its minute folding. Wherever the relationship between foliation and bedding could be distinguished, the two were essentially parallel. The conglomerate pebbles involved in the metamorphism are flattened normal to the bedding and elongated parallel to lineation. The microcline porphyroblasts appear to have been growing during the period of shearing when the lineation was developed, as all have been well rounded though they are free of cataclastic effects.

Younger Metamorphic Complex

Paracotos Formation

Description.—The writer proposes the name Paracotos formation for the group of less-metamorphosed phyllitic rocks which unconformably overlie the metasediments of the Caracas series. The extensive faulting in the region makes it impossible to designate a type locality for the entire formation, but a complete succession can be worked out from data obtained at various localities. The formation may be divided into the lower, middle, and upper Paracotos. The lower part of the lower Paracotos formation is best exposed in the blocks between the east-west trending faults, in the vicinity of El Pauji. The upper part of the lower Paracotos and the middle Paracotos beds can be observed directly south of Guayas on the road to Tiara, where it forms a large part of the mountain mass. The upper Paracotos rocks are best exposed between Cua and Tacata. The estimated minimum thickness of the Paracotos formation is 3500 m. The lower contact is a fault everywhere in the area studied.

In their work on the Coast Ranges of Venezuela, Aguerrevere and Zuloaga (1937, p. 23) consider what is here mapped as the Paracotos formation as part of their Villa de Cura series. This series included rocks from the supposed Charallave basal conglomerate upward through the San Juan de las Morros limestone. Detailed field work in the region, however, has shown that the Villa de Cura series, so defined, is too inclusive, as the Charallave conglomerate is in the Caracas series and some believe the San Juan de las Morros limestone is much younger, possibly Paleocene. To avoid confusion, the author has chosen not to redefine the term "Villa de Cura series", but has used the name "Paracotos formation".

Subsequent to its deposition, and prior to metamorphism, the Paracotos formation was intruded by hornblende diorite and soda granite, particularly in its lower parts. Intrusive serpentine is also found particularly within the upper Paracotos phyllites, not far above the middle Paracotos beds. Gabbro and basalt were emplaced locally subsequent to the metamorphism.

Lower Paracotos.—The minimum thickness of the lower part of the Paracotos formation is estimated to be 1300 meters in the area studied. The oldest beds of this sequence are green, chloritic phyllites, composed predominantly of chlorite and quartz, with accessory zircon, zoisite, garnet, and tourmaline, and locally interbedded with gray to black, thinly bedded limestone layers. A fair degree of schistosity and lineation are evident in most of the rocks, and some show intense folding. It is believed that this is the result of near-by faulting. Crosscutting quartz veins are locally abundant in this zone.

Above this phyllite is a series of microconglomerates composed chiefly of chert fragments, with a few quartz grains, in a green, chloritic matrix. The matrix is locally darkened by included graphite. Megascopically, this rock appears similar to the fine-grained facies of the Charallave conglomerate, but study with a microscope shows only minor shearing and recrystallization. The chert is very finely recrystallized but recognizable as original chert. No recognizable chert is found anywhere in the Caracas series.

An extremely fine-grained, greenish-gray phyllite zone, with a well-developed schistosity and indistinct "b" lineation, occurs above the microconglomerate. A typical specimen is composed of about 75 per cent of an almost isotropic, extremely fine-grained material, probably cherty silica. The X-ray diffraction pattern shows that this material has a high percentage of quartz. About 15 per cent of the rock is made up of rounded metamorphic quartz grains derived probably from the Caracas series rocks, together with finely recrystallized chert fragments. The remaining 10 per cent consists of what is believed to be a mixture of fine-grained chloritoid and sericite, but these flakes are too fine for precise optical determinations. Epidote and graphite occur locally in this rock in small amounts. Its texture and composition suggests that this phyllite may have been formed by metamorphism of a tuff or tuffaceous sediment.

Medium- to coarse-grained metagraywacke beds interlayered with this fine-grained siliceous phyllite are composed principally of finely recrystallized chert and quartz grains in a fine-grained siliceous matrix. About 10 per cent of the rock is made up of chloritoid; its common orientation results in a slight schistosity. A few fragments of plagioclase were noted, as were minor amounts of chlorite and a brown pleochroic mineral probably biotite. The quartz grains are not highly fractured and characteristically show ragged borders resulting from a secondary overgrowth of silica.

A thin bed of limestone, almost entirely fine-grained recrystallized calcite, occurs near the contact of the graywacke with the overlying middle Paracotos layers. It varies from a dark-gray, dense rock to white and coarsely crystalline marble. The phyllites between this limestone and the top of the lower Paracotos contain numerous quartz veins.

Although a lineation and foliation are not well developed in all the rocks constituting the lower part of the Paracotos formation, they are prominent enough to present difficulties in differentiating the phyllites from some of the adjacent Caracas series schists. The less competent Paracotos rocks generally show small repeated open folds and, except in localities adjacent to faults, have no further small-scale folding. Deformation along faults has locally impressed a second lineation on the phyllites, as well as highly contorting them.

Middle Paracotos.—The relatively resistant green beds making up the middle section of the Paracotos formation are quite distinctive, having a thickness of 1800 meters. They conformably overlie the phyllitic lower layers, although in many places the two are in fault contact. In its freshest outcrops, this rock with its green color, massiveness, and little schistosity or lineation, strongly suggests a tuffaceous rock. It is predominantly very fine chert, with numerous scattered flakes of chloritoid and sericite. Fine-grained epidote and chlorite give it a green color. A banded variety occurs where the rock is divided into epidote-rich and epidote-poor zones. Small amounts of crushed quartz, zoisite, and leucoxene are also found. It weathers to brown, shaley-looking material.

Although these beds are folded, there is noticeable lack of the more intense contortion found in the phyllitic types. Quartz veins are abundant in this layer, especially in the upper part. A few minor chert beds are also interlayered in the sequence.

These middle Paracotos beds closely re-

semble parts of the Tacagua formation in the Caracas region to the north (Dengo, 1953, p. 17), but it is not possible to establish the relationship between the two at the present time. Correlation may be postulated in several ways: (1) The Tacagua formation may be equivalent to the middle Paracotos beds. The fact that no unconformity has been found between the Las Mercedes formation and the Tacagua formation in the Caracas region (Dengo, 1953, p. 17) however, suggests that (2) the Tacagua rocks do not appear in the Los Teques region, and the Paracotos green beds do not outcrop in the Caracas region. (3) The Tacagua formation is made up of two somewhat similar green series, separated by an unconformity. (The writer favors this possibility.) The upper series, which appears to be lower in metamorphic grade, would correlate with the middle Paracotos, with a lower, more highly metamorphosed one, absent in the south.

Upper Paracotos.—The 450 meters of phyllitic shales, metamorphosed graywackes, conglomerates, and limestones constituting the upper part of the Paracotos formation conformably overlies the middle Paracotos beds. Near the contact, a calcareous, quartzose phyllite overlies and interfingers with the uppermost green layers. These are not highly foliated or crushed and do not have a well-developed lineation.

A thick sequence of light-brown graywacke containing rounded metamorphic quartz grains, rounded chert fragments, and a few plagioclase grains occurs above the phyllite. The matrix for this material is an extremely fine-grained chert, which has a rough schistosity due to the parallel growth of sericite and chloritoid. Accessory minerals include zircon, apatite, leucoxene, pyrite, magnetite, sphene, epidote, and brown tourmaline. Graphite is also locally abundant.

Well-rounded fragments of quartzite, graywacke, and chert make up the conglomerate beds that usually overlie the graywacke. The pebbles, with a maximum diameter of 25 cm., occur in a slightly schistose, purplish matrix. One pebble of fine-grained, recrystallized black limestone, apparently from the Caracas series, was noted. A chert conglomerate layer is also found here, consisting of rounded black chert pebbles, up to 10 cm. in diameter, in a cherty matrix. This rock shows some foliation, and most of the pebbles have been slightly elongated.

A layer of fine-grained, green limestone, about 15 m. thick, overlies these conglomerates. It is thinly bedded and not highly contorted. Although principally recrystallized calcite, it also contains numerous quartz grains and a little sericite. The youngest Paracotos beds observed in the region are brown phyllites, with an indistinct lineation and foliation, locally interbedded with the limestone. Quartz veins are numerous in this rock, and occasional calcite veins are also found.

Ultramafic Intrusive Rocks

The ultramafic bodies that intrude both the older and younger metasedimentary rocks can be divided into two groups on the basis of areal occurrence and petrology.

NORTHERN GROUP: The northern group of serpentines is made up of the six small outcrops found on the top and flanks of the main mountain mass between San Pedro and Agua Fria. The occurrences here are all in the Las Brisas formation at approximately the same stratigraphic horizon. At lower elevations and in other parts of the area, this same general horizon shows no such intrusions. These bodies are generally conformable with the foliation of the surrounding schists. In many cases one or both contacts of the serpentines are faults.

The dark-green variety of serpentine predominates in these northern outcrops, though it is frequently observed interbanded with a lighter-colored type. The resinous, highly slickensided "fish-scale" variety is less common. The usual diamond-shaped fracture pattern prevails in most of the outcrops, although unbroken blocks as large as a meter across may locally be observed. Much of this rock is composed of chrysotile serpentine, with serpophite also abundant. Chrysotile cross-fiber veinlets are numerous, as are large, platy bastite pseudomorphs after original enstatite. Fine-grained secondary magnetite is common.

The northernmost outcrop consists of a serpentinite composed largely of antigorite, with small amounts of serpophite and chrysotile. It is light green, hard, and resistant to weathering. Dengo (1953, p. 23) gives the analysis

of a specimen from the Caracas region similar to this antigorite-rich variety.

A hard, bluish, zoisite-rich zone is developed in the schists at serpentine contacts. The quartz in these aureoles appears to have been recrystallized to coarse grain size, and minor amounts of radial, acicular aggregates of tremolite have been produced.

SOUTHERN GROUP: The southern group of ultramafic intrusives consists of two small occurrences in the vicinity of Charallave and the thick sheet of serpentinized peridotite outcropping prominently between Tacata and Tiara, known as Loma de Hierro.

The Charallave serpentine bodies are lenses not more than several hundred meters long, composed of massive, dark-green rock showing the usual slickensided surfaces and deeply weathered cover. The serpentine mineral is mostly serpophite, with no remnants of the original olivine or pyroxene. The northern contact is a fault in both bodies, and the southern boundary is apparently an intrusive contact.

Loma de Hierro is a high ridge formed by a great sheet of serpentinized peridotite 700 ± meters thick. It was once thicker and was eroded prior to covering by the Tiara volcanics. This sheet is composed of massive, somewhat serpentinized harzburgite, having a fairly constant mineralogical composition throughout. A typical greenish-black specimen, obtained a short distance above the base, consists predominantly of mesh-structure chrysotile serpentine together with some serpophite. Prominent bastite pseudomorphs, after enstatite, locally up to 5 mm. long, are abundant, as are olivine and pyroxene relicts. Near the center of the exposures, an appreciable amount of isotropic, white, fine-grained interstitial material probably represents altered plagioclase. Accessory chromite and secondary magnetite occur throughout.

Although the Loma de Hierro ultramafic rock was conformably intruded into the phyllites of the upper part of the Paracotos formation, very little contact action is found. The phyllite appears slightly hardened at the contact. The sill as a whole has a slight suggestion of layering, believed due to differing degrees of resistance to weathering of zones having minor variations in composition. The entire body is highly jointed, slickensided serpentine coating the surface of many of the diamond-shaped fragments. The ultramafic has been intruded in its upper parts by pyroxene-bearing white dikes, which are probably related to the Tiara volcanic sequence.

The body is everywhere covered by a deep mantle of red clay, the surface of which is strewn with numerous rounded boulders of relatively fresh rock. Weathering and residual enrichment have developed lateritic iron, and, near the base of the weathered zone, nickeliferous clay minerals.

Hornblende Diorite

Intrusions of hornblende diorite locally cut the Paracotos metasediments. The diorite usually is dark green, equigranular, and medium- to coarse-grained with some crystals up to 5 mm. long. It averages about 45 per cent green-brown hornblende, 45 per cent oligoclase-andesine, 10 per cent quartz, and minor amounts of clinozoisite, apatite, magnetite, and pyrite. The percentage of quartz ranges considerably; some quartz-rich varieties probably owe their excess quartz to contamination by sediments. The plagioclase is generally subhedral; hornblende is both subhedral and anhedral. The hornblende has a negative $2V = 80°$, with $Z \wedge c = 18°$, and is pleochroic with X = pale brown, Y = light green, and Z = dark green. The plagioclase shows slight zoning and has been extensively saussuritized.

The diorite is generally not schistose, but most of the outcrops show at least a slight foliation and lineation. Little evidence of shearing is seen. The quartz grains may show undulatory extinction, and some of the larger phenocrysts have been fractured. The hornblende grains generally appear to resist shearing, though some develop an undulatory extinction or break into cleavage fragments.

Hydrothermal alteration has affected the diorite, particularly in its upper parts, and has changed the green hornblende to a colorless amphibole, altered the plagioclase, and locally produced abundant chlorite. Later veins of epidote and calcite are found.

A hornblendic border facies of the same intrusive forms small outcrops in the Paracotos

phyllite. The green hornblende, which generally makes up half of the rock, has been changed to colorless amphiboles, and the plagioclase is almost completely altered. As in the larger bodies, stringers of hornblende-rich material pass out into the surrounding phyllites as thin, hard, intrusive layers. Most of these stringers show very little shearing. Adjacent to the larger faults, particularly in the eastern part of the area, fine-grained epidote fills most of the fractures in this rock.

TABLE 2.—CHEMICAL ANALYSIS AND NORM OF THE SODA GRANITE, AR122

E. K. Oslund, Analyst, Rock Analysis Laboratory, University of Minnesota

Chemical Analysis		Norm	
SiO_2	69.74	Q	26.28
Al_2O_3	16.54	C	4.79
Fe_2O_3	1.05	Or	20.02
FeO	.45	Pc(Ab)	41.39
MgO	1.38	Hy	3.40
CaO	.65	Mt	0.70
Na_2O	4.92	Il	0.46
K_2O	3.40	Hem	0.48
H_2O^+	1.31	Ap	1.34
H_2O^-	.10	H_2O	1.41
TiO_2	.19		
P_2O_5	.06		
MnO	.03		
BaO	.10		
Total	99.92		100.27

The diorite intrusion also locally has a border facies of highly altered plagioclase (80 per cent) and augite (20 per cent). The slightly pleochroic pyroxene is purplish, and 2V (+) = 60°. It generally occurs with small amounts of microcline, quartz, ilmenite, and sphene. Fractured and bent plagioclase grains, rims of colorless amphibole on the pyroxene crystals, and the development of an overall schistosity show that this rock has been metamorphosed.

The relationship of the hornblende diorite to the ultramafic intrusions could not be determined, but it is believed that they are nearly contemporaneous.

Soda Granite

Following the emplacement of the diorite and prior to the youngest regional metamorphism, a minor amount of soda granite was intruded into the hornblende diorite and adjacent Paracotos and Las Mercedes rocks. It generally occurs as sheets and veins seldom reaching stratigraphically higher than the middle part of the Paracotos formation. It is usually gray and shows moderate schistosity and lineation. The grain size averages about 2 mm., with some of the quartz as large as 6 mm. Slightly zoned albitic plagioclase commonly makes up about 75 per cent of the rock; 25 per cent is crushed quartz. Nowhere is the rock completely fresh; the feldspar generally has been altered to sericitic mica. Some of this more highly altered feldspar may have been orthoclase. Accessory sphene, apatite, and zircon are also present, in addition to later epidote veins. In both megascopic and microscopic textures, this rock shows severe crushing and shearing, even where the surrounding rocks are not highly deformed. The quartz appears to break up very easily, showing the results of strain under relatively low shearing stress. Where crushed, this rock has a chalky appearance and is considerably lighter-colored than normal.

In some places, this granite intrudes the Paracotos formation in a *lit-par-lit* manner, as, for example, just south of Guayas on the road to Tiara. Here the injected tuffaceous middle Paracotos beds form distinctive white and green laminated exposures. Post-intrusion metamorphism sheared this rock mixture so that most of it is now a fine-grained mylonite. The small grain size prevents ready mineralogic determinations, but, where they are possible, they show the presence of fine-grained quartz, albitic plagioclase, microcline, and minor amounts of epidote, garnet, zircon, and leucoxene. Layers of muscovite and sericite produce a well-defined foliation. A chemical analysis of this rock (Table 2) shows that, although it has roughly the composition of a soda granite, the presence of corundum in the norm suggests contamination by Paracotos sediments. Some of the fine-grained material mapped as intrusive may be sedimentary quartz-feldspar layers in the Paracotos formation, which, because of the extreme shearing, are indistinguishable from the mylonitized granite. In favorable localities, uncrushed mixtures of granitic and Paracotos rocks

include rounded chert grains and large orthoclase phenocrysts in a granitic matrix. Some of this material still retains the greenish, epidote color characteristic of the Paracotos tuffaceous beds.

Granite dikes up to 20 m. thick are found north of Tacata and Charallave, commonly accompanied by numerous quartz veins. Coarse muscovite flakes, up to 2 cm. across, occur in these dikes and coat fracture and cleavage surfaces in surrounding diorites and metasediments. This granitic material has also locally been introduced into the Las Mercedes formation; the calcareous schists and Charallave conglomerate contain stringers and small injections. Almost all the southern outcrops of these schists contain coarse muscovite introduced along cleavage surfaces, but the dikes and stringers of actual igneous rock are rare. A small amount of glaucophane is common in these eastern granites.

The soda granite may be a late differentiate of the hornblende diorite intrusion, inasmuch as the granite is closely associated with the diorite in both time and space.

Deposition and Metamorphism of the Young Complex

The character of the Paracotos formation, the sedimentary portion of the Younger Metamorphic Group, strongly suggests deposition under geosynclinal conditions (eugeosyncline of Kay, 1944). The formation is made up of a great thickness of poorly stratified cherts, tuffs, conglomerates, and graywackes, presumably deposited in a relatively short time and reworked very little. Fossils are notably absent, as are thick limestone beds. The lowest part of the Paracotos observed in this region is typical graywacke, now forming the lower chlorite-rich layers. No basal conglomerate is found here, but, where one does outcrop on the road between Guatire and Caucagua, it consists predominantly of fragments from the Caracas series metamorphics and chert pebbles. The Paracotos formation grades upward into cherty phyllites, which are believed to represent the early stages of volcanic activity. Irregular layers of cherty conglomerate are abundant in this part of the formation. A few thin limestone zones are found in the upper part of this lower Paracotos sequence. The accumulation of the thick, massive green tuffs and cherts of the middle Paracotos indicates widespread volcanism at this time. This was followed by renewed graywacke deposition, irregularly intermixed with conglomerate and shale. Many of the conglomerate pebbles of these rocks apparently were derived from lower beds in the Paracotos, and most of the quartz in the graywackes probably originated in the Caracas series or Sebastopol gneiss. The lenticular limestone bodies in the highest part of the section suggest return to conditions sufficiently stable to allow deposition of organic reef material.

Prior to its metamorphism, this series was intruded by hornblende diorite, a related soda granite, and harzburgitic ultramafic material. This was then subjected to a low-grade metamorphism, and most of the metasediments were converted to phyllites. Other than by shearing, the granitic igneous rocks were little altered. The development of chlorite, epidote, chloritoid, and sericite in the Paracotos suggests that the metamorphism altered them predominantly to the muscovite-chlorite subfacies of the greenschist facies (Turner, 1948, p. 94). The presence of fine flakes of biotite in some of the northern outcrops of the Paracotos formation indicates a slightly higher grade of metamorphism here equivalent to the biotite-chlorite subfacies.

Chloritoid is abundant in this formation. In his discussion of the chlorite zone, Harker (1932, p. 213) considers the development of chloritoid characteristic of rocks rich in alumina and poor in magnesia, lime, and potash. He considers it a stress mineral, formed in the low stages of regional metamorphism in the presence of kaolin. The rocks of the Paracotos formation closely fit this description. The entire suite of minerals found in this rock unit are included in Harker's chlorite zone.

Serpentinized ultramafic subjected to metamorphism of the muscovite-chlorite subfacies are not antigoritized, nor generally are those in the northern area of slightly higher grade of metamorphism (Hess, Dengo, and Smith, 1952). Antigoritization begins near the northern margin of the Los Teques area and is complete farther north in Dengo's Caracas area, where the metamorphism cannot have been higher than the epidote amphibolite facies and

probably was a little lower. Thus the grade of metamorphism at which antigoritization occurs is well bracketed.

TABLE 3.—CHEMICAL ANALYSIS AND NORM OF THE TIARA BASALT, AR233

James J. Engel, Analyst, Rock Analysis Laboratory, University of Minnesota

Chemical Analysis		Norm	
SiO_2	46.26	Or	15.57
Al_2O_3	14.75	Pc Ab(26)	9.43
Fe_2O_3	1.06	Pc An(74)	27.24
FeO	8.39	Di Wo	5.80
MgO	10.49	Di En	3.90
CaO	8.71	Di Fs	1.45
Na_2O	1.06	Hy En	7.10
K_2O	2.58	Hy Fs	2.64
H_2O^+	4.44	Ol Fo	10.50
H_2O^-	.12	Ol Fa	5.92
CO_2	.06		
TiO_2	1.53	Ap	0.67
P_2O_5	.30	Il	2.89
MnO	.32	Mt	1.62
Total	100.07		

UNMETAMORPHOSED ROCKS

Tiara Volcanics

A series of mafic volcanic rocks which have not suffered dynamometamorphism overlies and intrudes the metamorphic rocks of the southern part of the region. Outcrops of both coarse-grained gabbroic and fine basaltic varieties are found; the gabbro represents sills and dikes equivalent to finer-grained basaltic extrusives. The thickness of this sequence could not be determined in the area mapped, but exposures total more than 900 m.

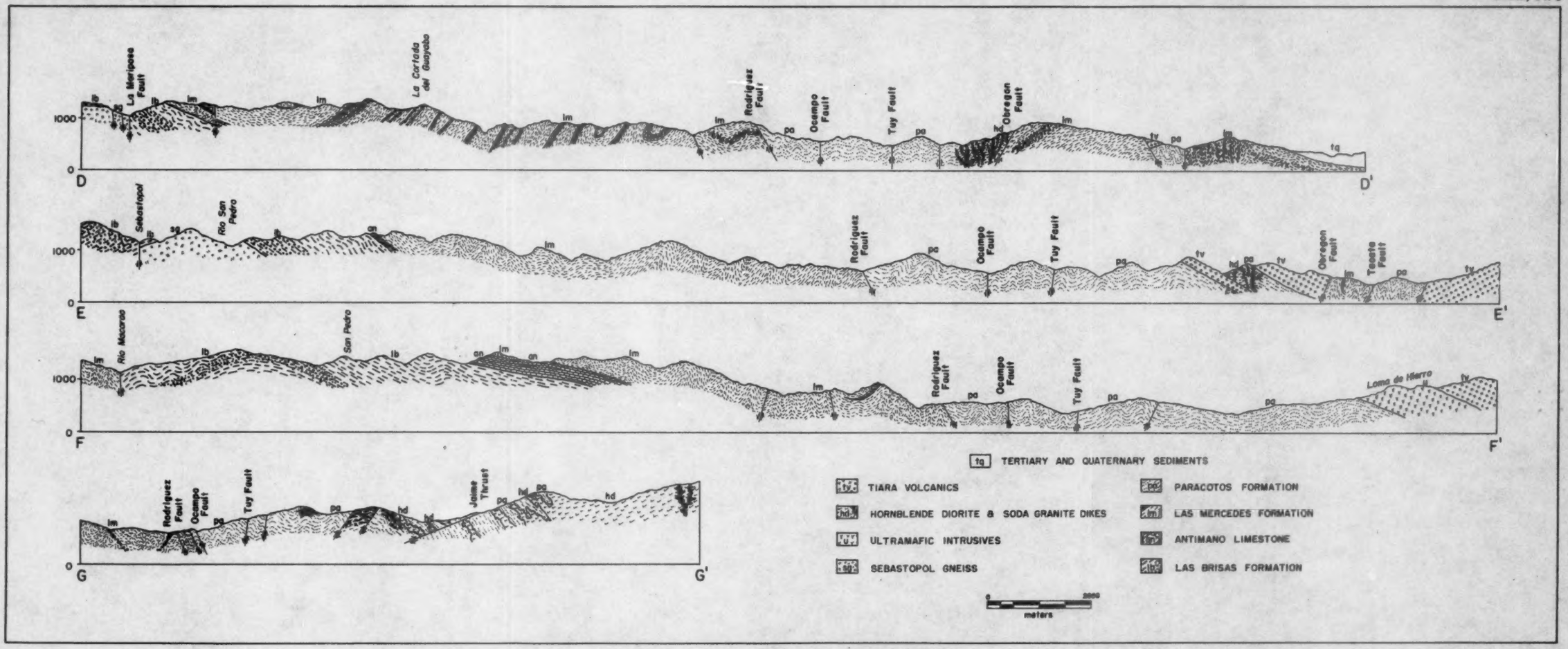
Outcrops of the coarser-grained gabbroic material are most abundant in the lower part of the sequence. The gabbro consists of ophitic augite and plagioclase in approximately equal amounts. The augite has $N_y = 1.685$, $2V(+) = 51°$, and exhibits a particularly well-developed, almost micaceous, (001) parting. Many crystals attain diameters of 10 mm., but most are smaller. A rough banding due to variations in crystal size is seen in parts of the rock. Serpentine, probably pseudomorphous after olivine, forms 2–3 per cent of the rocks, and chlorite is sparingly present. The borders of some of the pyroxene grains are altered to colorless amphibole, and the plagioclase is almost everywhere largely altered to clay minerals. This hydrothermal alteration, which shows particular preference for the plagioclase, is so all-pervasive that it suggests deuteric alteration, perhaps as a result of intrusion of water-rich sediments and submarine eruption of the flows. Although most of the rock is unsheared, a slight linear structure and protoclastic texture are locally developed, probably related to later faulting.

Gabbro dikes as much as 2 m. thick intrude the Loma de Hierro serpentine body. These have been peculiarly contaminated by serpentine, which has produced a texture much coarser than elsewhere—crystals with diameters of 2 cm. are common. The original olivine has been replaced by fine-grained tremolitic amphibole. The ultramafic side of the contact is completely serpentinized; relicts of pyroxene and olivine are absent.

The finer-grained, basaltic portions of this volcanic sequence overlie the gabbroic varieties. These are generally dense, light gray to black, and are subophitic. Some contain large plagioclase phenocrysts. This finer-grained material has also been hydrothermally altered; most of the augite has changed to a light-green amphibole, and the plagioclase to clay minerals. In addition, calcite, epidote, and prehnite are common, and most of the ilmenite has gone to leucoxene. These rocks show little evidence of layering or banding, and very little shearing and fracturing.

Table 3 shows the chemical analysis of a specimen of basalt obtained from an outcrop on the east bank of the Tuy River, immediately south of Tacata. It departs from many olivine basalts in its abnormally high K_2O and H_2O+ content. This suggests alteration comparable to spilite, but in this case with enrichment in K_2O rather than Na_2O.

Locally, a greenish-black sedimentary series made up of volcanic agglomerate, tuff, and a small amount of graywacke is closely associated with the Tiara igneous rocks. The agglomerate consists chiefly of angular fragments of the coarse- and fine-grained mafic rocks previously described, in addition to crystal frag-



STRUCTURAL CROSS SECTIONS

ments of plagioclase, pyroxene, chlorite, and hornblende. Preferred orientation of both the rock and mineral fragments suggests clastic deposition. The tuffaceous portions are made up predominantly of an opaque groundmass with scattered fragments of fine-grained plagioclase, quartz, and chert. These all have apparently been derived from the underlying volcanic and metamorphic sequence. This rock shows slight fracturing associated with faulting, and the fractures are filled by calcite and quartz. Because of their close association with the Tiara volcanics, these volcanic sediments have been mapped as part of that unit, even though they are probably slightly younger. Lithologically, they closely resemble portions of the Arrayanes formation (Mencher, 1951, p. 13) found along the southern flank of the mountain system.

Tertiary and Quaternary Sediments

A relatively thin cover of undifferentiated Tertiary and Quaternary sediments unconformably overlies the metamorphic rocks in the Tuy Valley. These consist largely of conglomerates, with subordinate clay, sandstone, and fresh-water limestone. The conglomerates contain mainly well-rounded metamorphic pebbles, some attaining diameters of 30 cm. The green and brown clay layers are locally quite thick and appear to be unbedded. The medium-grained, buff-colored sandstones are the most resistant rocks of the group and in some places form small ridges. Thin, unfossiliferous gray limestone lenses are found locally. Caliche, possibly remaining from a previous arid cycle, caps most of the hills.

Over most of the basin, these sediments have very slight dips. Near fault contacts with the metamorphics, they may be highly folded and faulted, suggesting that deformation continued until very recently and is possibly still going on. Their contact with the unmetamorphosed Tiara volcanics is not exposed in the area, but, as the igneous rocks have been much disturbed and these sediments have not, there must be an angular unconformity between the two.

The unconsolidated nature of much of this material, as compared with adjacent known Tertiary deposits, suggests that most of it is Pleistocene and Recent. The underlying Tertiary rocks are divided into the late Oligocene Ocumare formation and the early Miocene Cumaca and Aramina formations, which are unconformably overlain by the late Miocene Tuy formation; all are nonmarine. The Pichao conglomerate, which crops out 15 km. east of the mapped area, is possibly of early Miocene marine origin (Aguerrevere and Zuloaga, 1937, p. 11).

Structure

Folds

Except for the Tertiary and Quaternary sediments, all the rocks in the Los Teques-Cua area show evidence of some folding. These features range from microfold lineation to the major anticlinal structure. The map shows relatively few symbols for folds, since most are on a scale too small and complex to record. The primary problem here, therefore, was to attempt to analyze these minor features to arrive at a valid overall regional picture.

The area consists of a large, almost symmetrical though intensely faulted anticline, the axis of which crosses the northern part of the area with a trend of approximately N.75°E. Smaller anticlines and synclines have developed parallel to this major structure, together with numerous large isoclinal folds. Complete isoclinal folds, as shown on structure section (Pl. 3), are not observable in the field, but their presence is shown by a continued repetition of the same sequence of limestone beds, with very little change in dip. The folds developed in this case in relatively incompetent beds overlying more competent ones.

The schistose parts of the Caracas series have been subjected to even smaller-scale folding, grading downward from amplitudes measurable in meters to microfolds producing the pronounced lineation. The Paracotos rocks have suffered folding to a much less extent, but consistently show microscopic flexures (Pl. 2). Folding is also noted in the Tiara volcanic rocks, which locally are tilted through 35°. These unmetamorphosed rocks, however, do not show the minor crumplings characteristic of the schists. Drag folding accompanying faulting is common. However, effects directly

related to faulting cannot always be distinguished from those originating in the regional metamorphism.

The rapid downcutting by youthful streams into the topographically highest part of the region along the center of the major anticlinal structure suggests that the anticlines are still rising and the forces that produced the metamorphism and initial structural pattern are still active. The fact, however, that most of the transcurrent faults in the area are probably still moving means that at least some of the apparent anticline rejuvenation may be attributed to these. Whether the movement represents relaxation and isostatic uplift, strike-slip shearing parallel to the range, or both, is a matter of speculation.

Although crumpling has been intense, we can estimate the amount of shortening due to the folding of the Caracas series rocks. Prior to metamorphism, the schists now measuring 25 km. on structure section D-D possibly covered about 60 km.

Faults

Work in the Los Teques-Cua region shows that faulting also figures prominently in the structural history of the Coast Range. Of predominant importance are the intense transcurrent shear zones crossing the area in a N.80°E. direction, topographically evident as wide, linear valleys. The Tuy, Rodriguez, and Ocampo faults are examples of these. The main slip surfaces do not outcrop because of the deep weathering, but it is believed that most are steeply dipping and may be almost vertical. Fault-line scarps suggest that the Rodriguez fault has a southerly dip and the Tuy fault a steep northerly one. Wide crush zones border each major shear, and the rock becomes increasingly mylonitized in the proximity of the main break. The Obregon and related faults in the southern part of the area also appear to be essentially strike-slip features, although stratigraphic evidence suggests considerable vertical movement. These features could also be interpreted as thrust faults.

The direction of movement of the strike-slip faults has not been definitely determined in the area. The rock types on either side are usually quite different; in no case is it possible to find corresponding layers. The vertical component of movement and the high degree of folding are further complicating factors. Attempts to find consistent drag features were notably unsuccessful. The schistosity does not behave like sedimentary bedding, but usually becomes extremely irregular in strike as a fault is approached and suddenly passes into a highly crushed zone. Mullion structures on the smaller faults paralleling the major ones, however, do offer some clue. These show that, in addition to a large horizontal component, there has also been some vertical displacement. In most of the faults the north side has apparently moved relatively eastward and upward. Physiographic evidence is also seen in the stream pattern (Fig. 2). Almost all streams are offset at the faults, with the northern side displaced to the east. Very possibly a stream such as ABCD once flowed directly south from D to A.

A second system of faulting, trending N. 60°W., is prevalent. These fractures, as exemplified by the Tacata and La Mariposa faults, appear to have essentially normal-fault relationships. That there has been some horizontal movement, with the northern block moving southeast, is shown by the displacement of fold axes and distinctive layers and contacts by the La Mariposa fault. The Tacata fault also similarly offsets equivalent horizons in the Paracotos formation. The fault planes depart only slightly from the vertical in most places, but vary from this markedly where two join or meet one of the east-west trending variety.

Thrust faults with an east-west trend are developed in the Paracotos formation south of Guayas, the most prominent being the Jaime thrust. There are several good exposures of this thrust. It dips 24°N., and the near-by phyllites exhibit well-developed drag folds.

As with the folding, the entire area contains numerous small faults, of highly variable trends. These were not mapped or studied in detail.

Evidence for dating the beginning of movement is lacking, but there is considerable evidence that some faults are still active. Earthquakes are not uncommon in the region; strong ones have been recorded within historic time. In addition, alluvial fans are seen locally along the main faults; this, when combined with the widespread rapid stream erosion, suggests that

uplift is still going on. The Tertiary and Quaternary sediments also show minor folding and faulting adjacent to the fault contacts.

The pattern of the major faults suggests a relationship between the various types of movement. If it is assumed that the northern portion of the area is moving relatively eastward along N.80°E. faults, the tensional component would be directed approximately N.50°E. This means that the N.60°W. trending faults are probably tensional features, and they generally do exhibit normal-fault relationships as would be expected. The two sets of faults cut each other in many places, showing that they are contemporaneous and probably a result of the same forces.

Regional Deformation

Age Relationships

The metamorphic rocks in the Coast Ranges of Venezuela have not been dated with certainty. A summary of the facts has recently been presented by Dusenbury and Wolcott (1949, p. 17–26) and reviewed by Dengo (1953).

The alternatives are either that the metamorphic rocks were a basement upon which the Cretaceous sediments were deposited, or they have been developed by metamorphism of Cretaceous, and possibly slightly older, sediments. A concise summary of the situation is stated by Hedberg (1950, p. 1185):

"In Central Venezuela in the Barquisimeto area the Cretaceous sequence grades laterally into metamorphic rocks, and Cretaceous sediments occur within the Northern Range of Trinidad. It therefore would not be improbable to find some Cretaceous included in the Paria-Araya area. However, there is certainly equal probability of finding in this area the metamorphosed equivalents of the thick pre-Cretaceous (early Mesozoic?) section known below the Cretaceous in the Eastern Venezuela basin or the definitely confirmed Jurassic of the Northern Range of Trinidad. Phyllites lithologically similar to those of Paria-Araya are known to be associated with and to underlie the ammonite-dated Jurassic of the Trinidad Northern Range. Certainly the lithologic similarity of the known pre-Cretaceous sediments to the metamorphics is as great or greater than that of the Cretaceous rocks."

The latest proponents of a metamorphic basement theory are Liddle (1946) and Gonzales de Juana (1947). Their belief is partly based on the Jurassic age of some of the rocks in the North Range of Trinidad (Senn, 1940) and their similarity to the Caribbean series in Venezuela.

The alternative considers most of the metamorphics Cretaceous. Kehrer in particular (1937, p. 59–66) noted numerous localities where he had presumably observed a transition from unmetamorphosed to metamorphosed Cretaceous rocks. Other work which tends to support this correlation has been done by Aguerrevere and Zuloaga (1937), Renz (1942), Dusenbury and Wolcott (1949), Bucher (1949), Hess and Maxwell (1949), Maxwell and Dengo (1949), and Dengo (1953). Much of this conclusion is based both on the lithologic similarity of the metamorphic rocks to part of the unmetamorphosed Cretaceous section, and on the fact that no unmetamorphosed early or middle Cretaceous sediments have definitely been found unconformably overlying the metamorphic rocks. The comparison on the basis of lithology is not too satisfactory a method, as the pre-Cretaceous sedimentary section in this region is unknown.

Some evidence has been obtained to aid in the dating of these rocks. G. Pardo, in 1942, while mapping in the vicinity of San Sebastian for the University of Caracas, discovered a Cretaceous ammonite in the unmetamorphosed Arrayanes rocks. Careful study by Pardo and E. Mencher showed that it had not been reworked. This ammonite has been identified as *Peroniceras cf. moureti* De Grossouvre by A. A. Olsson, and given an early Senonian age. Other identifications confine it to the Coniacian. H. H. Hess, in a heavy-mineral study of the matrix material surrounding the fossil (personal communication), noted the presence of an abundance of the same peculiar pyroxene, characteristic of the Tiara volcanic sequence, that has a pronounced, almost micaceous (001) parting. In addition, chromite was present, undoubtedly originating in the serpentine rocks intrusive into the Paracotos formation. These facts, therefore, indicate that both the unmetamorphosed Tiara volcanic rocks and the serpentines were emplaced and were being eroded before the deposition of this ammonite-bearing bed. This dates the metamorphism of the Paracotos formation as preceding the end of Coniacian time.

Wolcott (1943, p. 1632) found macrofauna in what is now considered the Zenda phase of the Las Brisas formation (Hess and Dengo, unpublished report). The fossils came from small, black limestone lenses associated with a quartzite zone cropping out in the Quebrada de Cara, east of the village of Guarenas. Poor preservation prevented accurate determination. The presence of definitely identifiable *Pecten* (*Camptonectes*) sp. limited the rocks to the Jurassic or Cretaceous.

More recent work by Wolcott in the vicinity of Capaya, near Caucagua, resulted in the discovery of recognizable Foraminifera in a gray limestone layer (Dusenbury and Wolcott, 1949). This rock was considered to be Los Colorados limestone, and the descriptions fit the type section as observed in the Los Teques region (although the material may be one of the limestone lenses in the Paracotos formation). The microfauna, although poorly preserved, suggests a Turonian age, more or less equivalent to the Querecual formation of the Guayuta group.

Of considerable importance was the discovery by H. H. Hess of a fossiliferous limestone pebble in one of the slightly metamorphosed conglomerate horizons of the upper part of the Paracotos formation. This dark-green, massive fragment occurred in a hematite-stained matrix of fine-grained quartz and clay, together with numerous graywacke pebbles, approximately 6 km. north of Charallave on the road to El Valle. The composition and nature of the metamorphism of the pebbles of this conglomerate suggest that most originated from lower parts of the Paracotos formation, rather than from the Caracas series. Dr. H. H. Renz of the Mene Grande Oil Company identified the fossils as follows:

Gümbelina sp. (common)
Globigerinidae (common)
Globotruncana sp. (aff. *apenninica* Renz)
Other indeterminable Foraminifera (common)

Renz believes the rock is of Late Cretaceous age, possibly Cenomanian. This would make the pebble equivalent in age to the lower Querecual or lower La Luna formations.

Examination of outcrops of the Los Colorados type limestones in the vicinity of El Pauji resulted in the discovery of numerous fragments of poorly preserved microfossils. According to Renz, these cribrate and reticulate fossil remains are distinctly reminiscent of certain limestones in the El Cantil formation of eastern Venezuela. Work in similar limestones in the vicinity of Baruta by Maxwell and Dengo (personal communication) yielded unidentifiable highly crushed macrofossils.

Assuming the relatively meager amount of fossil evidence to be essentially correct, the metamorphic rocks in the Los Teques region can be dated and correlated as shown in Table 4. If these results are valid, a very complex geological history has been compressed into a relatively short time interval. The Caracas series was probably deposited in Neocomian to Cenomanian time; these rocks were then metamorphosed and were supplying material to the Turonian Paracotos sediments. Metamorphism of the Paracotos, and the intrusion of ultramafic material, occurred within the Turonian, followed by emplacement of the Tiara volcanics.

The Paracotos rocks were intruded by ultramafic igneous rocks and metamorphosed prior to the intrusion and extrusion of the Tiara volcanics. All these preceded the deposition of the ammonite-bearing beds of the Arrayanes formation in Coniacian time.

Tectonic Interpretation

The idea of a crustal downbuckle as the explanation of island-arc features was first applied to the Caribbean region by Hess (1938). More recent work in the southern Caribbean (Hess and Maxwell, 1949) has shown that the two belts of downbuckling are not continuous, but a portion of one formerly passed through northern Trinidad and Venezuela, ending near Barquisimeto, while the other begins near the island of Orchila and passes westward, just north of the Dutch islands of Bonaire, Caracas, and Aruba. The forces causing the tectogene in Northern Venezuela and Trinidad appear to have ceased, allowing the downbuckled zone to rise isostatically and form the North Range of Trinidad and the Coast Ranges of Venezuela.

The writer postulates the following sequence of events in the Los Teques region, as interpreted in the light of this tectogene hypothesis. The Caracas series platform sediments accumu-

lated on the granitic Sebastopol basement during the early Cretaceous, at which time the crustal downbuckle was initiated in the Caribbean region. The rocks just deposited became these sediments. This sequence of rocks, including the Paracotos formation, then underwent metamorphism, less intense than that affecting the Caracas series, with the formation of phyl-

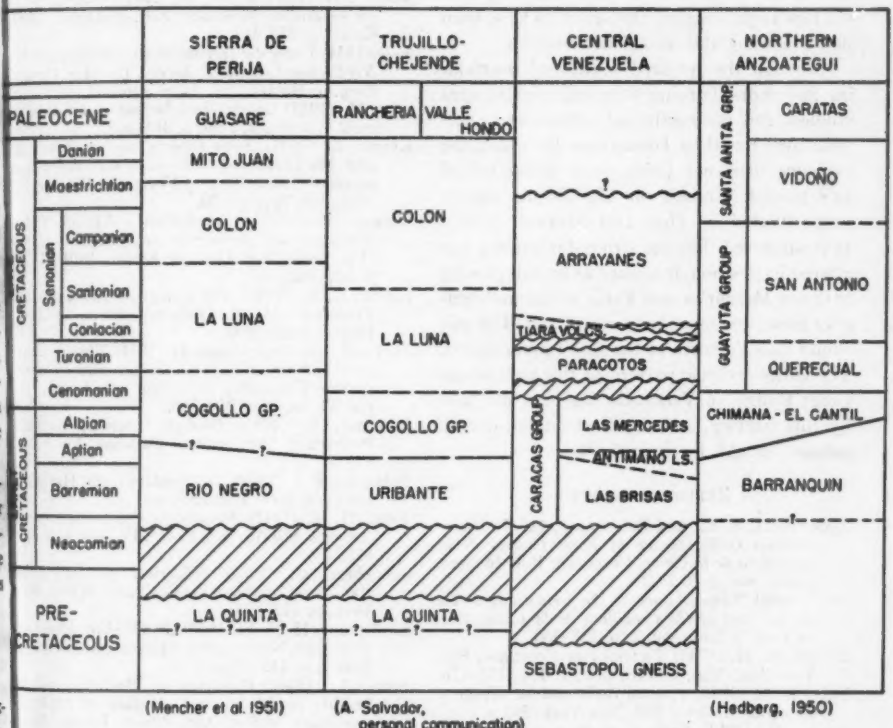


TABLE 4.—CRETACEOUS CORRELATION IN VENEZUELA

Unmetamorphosed sections taken from the chart prepared by the Comision de Geología del Congreso del Petroleo, 1950. E. Mencher, K. F. Dallmus, H. J. Fichter, C. Gonzalez de Juana, L. Ponte R., H. H. Renz, P. de Schumacher.

metamorphosed and highly folded as a result of this deformation. After a geologically short period, the forces relaxed enough to allow these metasediments to rise and undergo local erosion. This uplift was short-lived, however, and was almost immediately followed by further subsidence and the rapid deposition at the Paracotos formation in a eugeosyncline. This sequence was formed largely of fine sediment of volcanic origin with much included chert, no doubt also related to the volcanics. It also contains debris eroded from the Caracas series. Granitic and ultramafic igneous rocks invaded lites rather than schists. Gabbro and basalt were intruded and extruded and were being eroded when the Arrayanes formation was being deposited to the south in Coniacian time. Upbowing and faulting have probably continued sporadically since then. The several strong Tertiary deformations well known from eastern Venezuela probably affected this area, but evidence of these events is lacking here.

The sequence of events in this region suggests the validity of the tectogene theory. Several ideas as presented by Hess (1938), however require alteration. In the area mapped, the

serpentine bodies are not limited to two bands, but appear to occur indiscriminately though within a broad east-west belt. Further, these rocks appear to have been intruded not with but soon after the first intense deformation. In the Los Teques region, this seems to have been just preceding the second deformation.

Although the required southward overfolding and thrust faulting were found in the area studied, and the northward thrusts and overfolds were found by Dengo near the coast, the evidence does not point to a geotectoclinal axis passing through the Los Teques region, as postulated by Hess and Maxwell (1949). It is suggested that the strike-slip faulting has altered its position, inasmuch as an axis passing between Margarita and Paria would undoubtedly have been offset numerous times. The axis would thus lie north of the Los Teques region. The entire tectonic pattern in this part of the Coast Ranges of Venezuela has been modified by this faulting, and its effect on the overall picture should be investigated.

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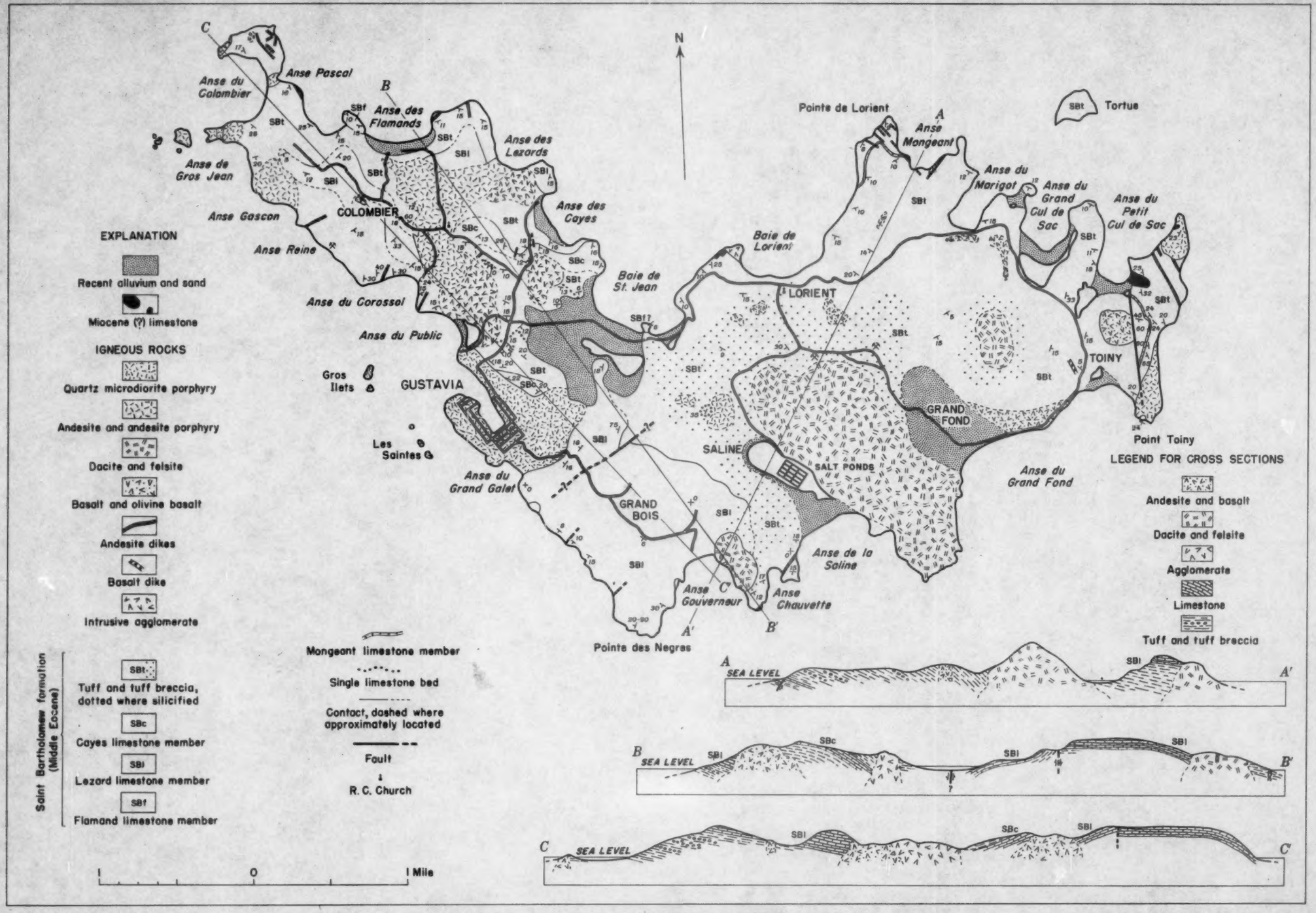

GEOLOGIC MAP OF SAINT BARTHOLOMEW

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GEOLOGY OF ST. BARTHOLOMEW, ST. MARTIN, AND ANGUILLA, LESSER ANTILLES

BY ROBERT A. CHRISTMAN

ABSTRACT

The islands of Saint Bartholomew and Saint Martin consist of andesitic tuffs and tuff-breccias of Middle and Late Eocene (?) age, respectively, which have been intruded by hypabyssal basalt, andesite, and quartz diorite of a slightly later age. No older "basement rocks" are present as previously supposed. During the late Eocene and early Oligocene, these islands are believed to have been the sites of active volcanoes whose centers of activity shifted from east to west. The tuff series were tilted and faulted as a result of the volcanic activity and on St. Martin they were extensively metamorphosed.

By the end of the Oligocene, the area had been eroded to the roof level of the intrusive rocks and the Oligocene-Miocene limestone and marls were deposited unconformably on the tuffs. On Anguilla, limestone of a similar age covers the entire island except for two small outcrops of tilted tuffs and basalt.

At some later date, the limestones were gently folded, and, during the Pliocene and Pleistocene, the islands were probably connected to form one large island. The area is now submerged to form the Anguilla bank with the mountainous portions being the present islands.

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Introduction

The islands of Saint Martin, Saint Bartholemew, and Anguilla are located on Anguilla Bank. These islands lie to the east of the Lesser Antilles active volcanic arc and form a part of an outer arc, the "Limestone Caribbees" (Fig. 1). The Anguilla bank (Fig. 2) has an area of 1800 square miles of which only 90 square miles are above water. It is separated from the Antigua-Barbuda bank to the southeast by a channel 18 miles wide and with a maximum depth in excess of 130 fathoms. Saba, an island of the volcanic arc, lies 20 miles to the southwest across a channel nearly 500 fathoms deep. The island of Sombrero is on a bank an equal distance to the northwest and depths of almost 400 fathoms are found between these banks. To the north and northwest of Sombrero, the Anegada passage forms a deep gash in the submerged topography, separating the Lesser Antilles on the south from the Virgin Islands and Greater Antilles on the west.

Anguilla bank is covered for the most part by about 30 fathoms of water. Around most of its perimeter, the slope of the bottom increases abruptly at approximately the 40 fathoms contour, dropping off steeply into deep water. It seems very likely that the bank has at times in the past been a single large island.

The purpose of the present study was to obtain information on the geologic history of the Lesser Antilles in order to understand the development of the great crustal structure producing the large negative gravity anomalies which parallel the Lesser Antilles arc to the east. Previous investigators have reported "basement" rocks presumably of late Cretaceous age on several of these islands. It was supposed that these older rocks corresponded to Cretaceous rocks found along the central axes of Puerto Rico and the Dominican Republic. If this were the case, the characteristic serpentinized peridotite intrusions should probably be found in them. The results of this investigation, however, indicate that the above concept of a Cretaceous "basement" is incorrect.

Acknowledgments

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J. C. Maxwell deserves special thanks for the guidance and assistance he gave to the completion of this report. The writer is indebted to Professor H. H. Hess, who suggested and supervised the study, and to the other members of the Princeton faculty who have been most helpful. The field assistance by Charles Rose during 1948 is gratefully acknowledged.

On each island there were numerous inhabitants who were most hospitable to the writer. Among these, Fathers Weyers and Boradori on St. Barts and Mrs. Wathey on Saint Martin deserve special thanks.

The writer is especially grateful for the paleontological assistance received. Dr. W. Storrs Cole and Dr. J. W. Wells of Cornell University identified a limited collection of Eocene Foraminifera and Tertiary corals, respectively. Dr. H. G. Richards of the Philadelphia Academy of Sciences identified the Tertiary mollusks and Dr. C. Wythe Cooke of the U. S. National Museum identified several Tertiary echinoids. C. W. Drooger of the Geological Institute at Utrecht, Holland, kindly studied the Oligocene-Miocene Foraminifera.

This paper is a condensation of a report submitted to Princeton University in partial fulfillment of requirements for a Ph.D. degree. The complete manuscript is deposited in the Library of the University.

PART 1—GEOLOGY OF SAINT BARTHOLOMEW

General Statements

The island of Saint Bartholomew (St. Barthélémy, or more simply, St. Barts) is a French colony under the jurisdiction of the governor of Gaudaloupe. It is the most southeastern island of the Anguilla bank, being about 14 miles southeast of St. Martin, the largest island. St. Barts has the shape of a boomerang with a maximum width of about 2 miles and a length of 6 miles and an area of approximately 10 square miles.

For its size, the island has considerable relief, the area northeast of Grand Fond having an elevation of about 1000 feet. At lesser elevations, there are many high peaks scattered throughout the island giving it a rugged topography. In general, the island represents the uplands of a submerged mountainous area. Its coast line is embayed with sharp, precipitous cliffs on the southeast side. Surrounding St. Barts are many small rocky islands, only a few of which are shown on Plate 1.

Previous Work

A number of geologists have spent a few days on St. Barts. In most cases, they were concerned with collecting fossils for age determinations of the Saint Bartholomew limestone. Little attention was given to the tuff series or to the igneous rocks. No detailed geologic map has been published so that the relationships between the rock types was not certain.

The earliest workers were P. M. Duncan (1863; 1873) and P. T. Cleve (1871) who attempted to relate the Caribbean history to that of Europe. In 1901, Spencer mentioned the island briefly in his study of the region, and later T. W. Vaughan (1918; 1926), Cushman (1919), and Cooke (1919) reported on their findings in this region. The most recent worker on St. Barts was the late Dr. Alfred Senn (1940). He recognized three limestone horizons and sug-

FIGURE 1.—INDEX MAP TO THE CARIBBEAN REGION

gested changing the name of the sediments from the St. Bartholomew limestone to the St. Bartholomew formation, since the "limestones occur only as intercalations in the great thickness

stitut Geographique National in Paris and used for the compilation of the final map. The topography on the cross sections, which accompany the geologic map, is only approximate.

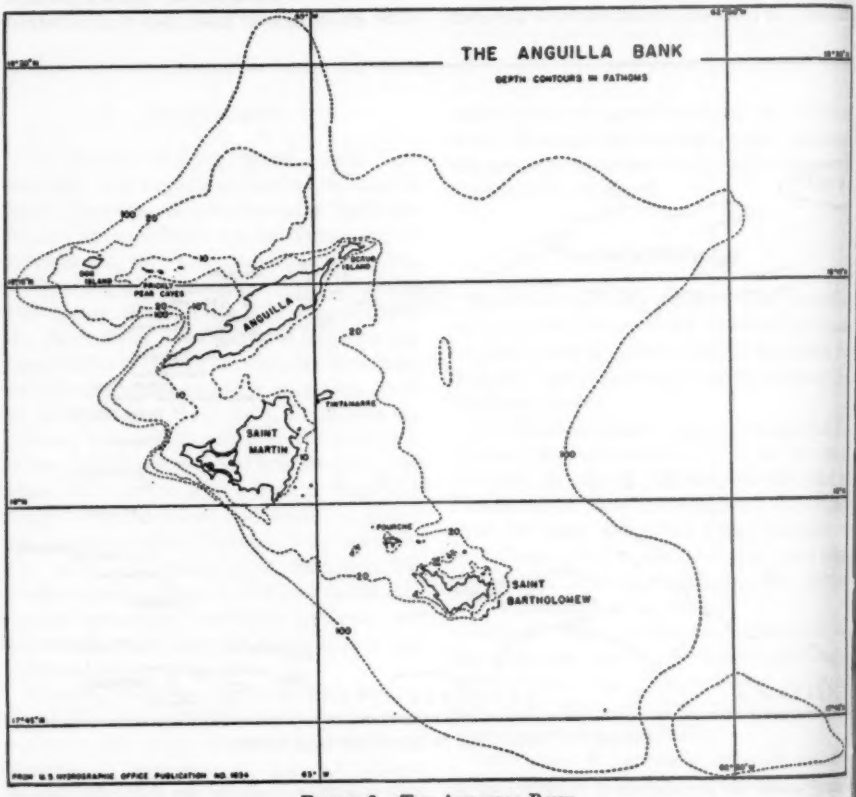

FIGURE 2.—THE ANGUILLA BANK

of volcanic tuffs and agglomerates". His collection of fossil Foraminifera is being studied by Dr. Storrs Cole of Cornell University.

Preparation of the Map

The field studies on St. Barts were conducted by the writer between August 13 and September 10, 1949. The geologic data were plotted on a map made by a local resident which was the best available. A week before completion of the study a sketch map was obtained from French aerial photographs at a scale of 1:33,700. Later these photographs were obtained from the In-

Saint Bartholomew Formation

General statement.—The bedded sediments on St. Barts consist of limestones which make good key beds and volcanics which do not. The volcanics range from fine-grained tuffs to coarse volcanic breccias and seldom can be traced because they lack distinguishing characteristics which are necessary in areas of poor outcrop. The problem of mapping these sediments becomes more difficult when coarse volcanics are encountered because bedding is usually lacking and in their weathered state they are difficult to distinguish from agglomerates. The writer in

tends to follow the definitions for volcanic deposits given by Wentworth and Williams (1932), restricting the term agglomerate to pyroclastics which have not been transported by water, hence to fillings in volcanic necks or material which has fallen near the volcanic vent. Unless the unit shows a discordant relationship or contains fragments fused together, the writer will use the less restricted term of "volcanic breccia".

The limestones make good beds for tracing local structure, but are rather discontinuous due to the intrusion of later igneous bodies. Since detailed mapping has shown the existence of four prominent limestone beds, Senn's (1940) division of upper and lower limestones is no longer adequate.

The sedimentary rocks of St. Barts are, therefore, a very complex and unwieldy group. The name "Saint Bartholomew formation" must be used to designate the entire series inasmuch as the various limestones and tuffs are essentially similar throughout the island. Where certain prominent limestones are referred to, they have been assigned a locality name, thus giving them the status of a member.

Eocene limestones.—The limestones on St. Barts are dense, black to dark gray, fine-grained rocks resembling those in the Paleozoic section of the Appalachians rather than common Tertiary limestones elsewhere. They are generally massive with beds 6 to 12 feet thick not uncommon although beds less than a foot thick occur where the limestones become tuffaceous. Along the coast the limestone weathers with a pitted surface. Inland it is smooth and forms resistant caps on hills and provides abundant float where outcrops are less well developed. It is less susceptible to weathering than are the tuffs and igneous rocks under the warm, relatively dry climatic conditions of the area. Certain zones in the limestones contain abundant Foraminifera, both large and small, as well as corals. Time did not permit the making of extensive collections. Adequate collections had been made by prev ious investigators.

The stratigraphic relationships of the various limestones are clearer in the northwest portion of the island then elsewhere. Senn (1940) referred to three limestones but later, in notes sent to Dr. Cole, he correctly eliminated one of them. The writer discovered additional limestones apparently not seen by Senn. The limestone members of the St. Bartholomew formation are named as follows from the bays on which they outcrop:

(4) Cayes ls.
(3) Lezard ls.——? ls. of the Grand Bois Plateau
(2) Flamond ls.
(1) Mongeant ls.

MONGEANT LIMESTONE MEMBER: This member is a convenient key bed about 30 feet thick occurring in the northeastern portion of the island. It can be traced from the northeastern side of the Baie de Lorient to the eastern side of Anse Mongeant where it is cut by small normal faults. It is again found in the ridge along the east side of the island north of Pointe Toiny. A bed in the upper portion of this member at both localities contains numerous coral fragments.

Overlying the Mongeant limestone is a thick series of fine-grained tuffs which disappear beneath the Grand Bois plateau area. Inasmuch as the other limestone members overlie these tuffs the Mongeant member is probably the oldest limestone on St. Barts. Fossil evidence, however, does not indicate any significant difference in age for this member as compared to the younger limestone members of the formation.

Corals from both areas of outcrop identified by Dr. Wells include: *Stylophora contorta* Duncan *non Leymerie.* Four thin sections examined for Foraminifera by Dr. Coles contained only *Lituonella* sp.

FLAMAND LIMESTONE MEMBER: This member, outcropping west of Anse des Flamand, consists of a lower limestone 80 to 100 feet thick lying upon a green tuff breccia. Above the lower limestone is about 100 feet of fine-grained green tuff which contains occasional volcanic rock fragments up to one inch in size. Upon this tuff rests on upper limestone about 40 feet thick which is overlain by more tuffs. Fossils are comparatively rare in the Flamand limestone. The following Foraminifera were identified by Dr. Cole:

Dictyoconus americanus Cushman
Fabiania sp.
Lepidocyclina (*Polylepidina*) *antillea* Cushman

This limestone member lies below Senn's "lower

limestone," but the fossils are similar to those found by Senn in the overlying section.

LEZARD LIMESTONE MEMBER: Proceeding eastward along the north coast the next stratigraphically higher limestone is the Lezard member which is Senn's "lower limestone." It is approximately 150 feet thick. Included in it are beds of fine-grained, white calcareous tuffs which have a sandy appearance, and beds of cross-bedded tuff conglomerates with volcanic pebbles up to 4 inches in diameter. The following corals were identified by Dr. Wells:

Astrocoenia incrustans (Duncan)

Hydrophora n. sp.

No limestone is present on the south side of Anse des Lezards where only intrusive agglomerate and andesite porphyry outcrop. Limestone is found again on the hill west of Anse des Lezards but westward it again gives away to andesite porphyry. High on the hill above the Flamand limestone, the Lezard limestone is present again, although thinner. This limestone thickens greatly to the west where it forms massive cliffs along the path to Anse du Columbier. Traced to the south it forms the capping of the large hill south of the village of Columbier.

The thickness of this member seems to vary between 50 and 200 feet, but in part this variation may be due to leaching of the carbonate by the hot solutions associated with the magmatic activity. South of the village of Columbier, several beds of brown, highly weathered calcareous material may represent these beds. A similar leached limestone adjacent to an andesite porphyry can be clearly seen north of Gustavia.

CAYES LIMESTONE MEMBER: This limestone is found on the promontory separating Anse des Cayes and Baie de St. Jean and is Senn's "upper limestone". It is about 100 feet thick. Along the coast the beds are striking N20°E and dipping 16°SE but eastward the dip becomes much steeper to carry the beds to the hill east of the Columbier R. C. church. Dr. Richards identified specimens of *Spondylus* and *Cardium* from this member.

LIMESTONES IN THE GRAND BOIS PLATEAU AREA: The high area south of Gustavia which extends to Anse Gouverneur is capped with flat-lying limestone, best exposed in the large sea cliffs between Anse du Grand Galet and Pointe des Negres. In the vicinity of Pointe des Negres, the dips of the beds become steeper and at the point are sharply folded, together with some interbedded green tuffs. On the west side of Anse Gouverneur, three prominent limestone beds dipping 30° southwest are interbedded with the fine-grained, light-green to gray tuffs and coarser volcanic beds with fragments up to 6 inches in diameter. Here a small andesite porphyry plug cuts the sediments. Another small intrusive mass is found near Anse du Grand Galet.

On the north side of the plateau area, the limestone forms a large cliff which, traced to the northwest, suddenly changes dip from nearly horizontal to 75°NW where it is cut by a fault. Other small faults were observed along the coast and the aerial photographs show a series of parallel valleys extending in the same northeastward direction which may be localized by similar faults. The limestone in this area is estimated to be at least 300 feet thick.

The correlation of the limestone in this area with those already described is not absolute, but the available evidence indicates that it is equivalent to the Lezard member. This requires postulating a 300–500 foot fault extending south from Baie de St. Jean to raise the beds in the eastern portion of the island to their present position. Any other correlation would not fit the sequence and the assumption that this limestone is either younger or older than the others would require a fault of several thousand feet.

OTHER LIMESTONES: The small peninsula of limestone extending into Baie de St. Jean is probably the Flamand member, since it lies beneath the Lezard limestone of the plateau area. On the east side of this bay, a thin limestone bed in the volcanics yielded two specimens *Astrocoenia d'achiardii* Duncan and an *Ostrea* sp.

The youngest limestone, lying above the Cayes member is found northeast of Monsieur Ledee's home and east of Baie de St. Jean. It is a tuffaceous, light-brown, thin-bedded limestone, from which a new coral specimen, *Cladocora*, was collected. This horizon is also found at the top of the hill about 2000 feet southwest of the Roman Catholic church at Columbier and again about 500 feet south of

where the road bifurcates to Lorient and Columbier north of Gustavia. Another specimen of the same coral was found here and Senn in his field notes describes this bed as "massive, light gray algal and hydrocoral limestone with small *Numulites* and *Lepidocyclina*".

AGE: Collections of fossils from the limestones on St. Barts, which have been studied by various paleontologists, all indicate either a middle or late Eocene age. No significant age differences have been noted between the various limestones.

Cleve (1871) in comparing the fossils with European forms called the beds middle Eocene; Duncan (1873) believed that the corals were deposited in an Eocene reef which may have transgressed the time boundary both above and below. Fossils collected from the island by Vaughan in 1914 were later studied by Cushman, Cooke, and others. Cushman (1919) indicated a late Eocene age and Cooke (1919) likewise considered the fauna closest to the late Eocene (Jackson stage).

Vaughan (1932) and Cole (1942) have reassigned the formation to the middle Eocene on the basis of the Foraminifera. Dr. Storrs Cole in a discussion of *Dictyoconus* says "The identification of specimens previously called *D. gunteri* and *D. codon* with *D. americans* opens the way for a correlation of the middle Eocene deposits between the Plaisance limestone, Republic of Haiti, the 'yellow limestone' of middle Eocene age at several localities in Jamaica, the St. Bartholomew fm., St. Bartholomew, Leeward Islands, and the middle Eocene of Florida". His unpublished studies have apparently not yet yielded any results to contradict this correlation.

Younger limestone.—Two small areas of younger limestone occur on the east side of Anse du Petit Cul de Sac. The larger is on the southeast side of the innermost part of the bay and is 500 by 200 feet in area. It appears to be "plastered" on the tuffs, as its outcrop forms a narrow tongue which does not extend to the top of the hill. The smaller one, about 100 by 200 feet in area, is found to the north almost at the point on the east side of the bay. It rests directly on an intrusive andesite porphyry which cuts the tuffs.

The limestone is composed of cream-white, well-rounded, oölitic-appearing grains of carbonate (89% by weight) and a small amount of quartz, felsite, and an occasional magnetite grain. The grains are of sand size and are very loosely cemented. In thin section the rock is seen to be composed of many poorly preserved Foraminifera, of the globigerina type. The rock should be classified as a "foraminiferal limestone."

Beds from a half to 3 inches thick were seen in a wind cave in the southern deposit, but otherwise the surface is pitted and has indistinct bedding. The northern deposit shows crossbedding and rests directly on jointed andesite porphyry. Rounded boulders of the andesite are found in the first few feet of the limestone.

Other than having the general appearance of a young deposit and being younger than the andesite which cuts the middle Eocene sediments, evidence of the age of these beds is lacking. A similar limestone occurs on Prickly Pear Cay west of Anguilla which is presumably Miocene. The dips of 23° and 28° seem rather high to be considered as primary and probably are a result of tilting. That the beds were deposited in a near horizontal position as a shallow-water, marine deposit is suggested by the cross-bedding and Foraminifera. Thus, after the emplacement of the andesite, the area was eroded, submerged, and later tilted. This tilting may be related to the fault which extends north-south through this region.

Post early Miocene movements are known in both St. Martin where the Low Lands formation is slightly warped and in Anguilla where the marls are faulted. Thus, on this slim evidence, it is believed that these small outcrops of foraminiferal limestone are Miocene in age, although a Pliocene or Pleistocene age is possible.

Pyroclastics.—Almost half of the area of St. Barts is covered with bedded pyroclastics. As they are interbedded with limestone, they were probably deposited largely in water, although some show evidence of having formed above water. They vary greatly in their physical appearance, with a range in grain size from fine tuffs to coarse breccias or agglomerates, and with a color range from white to dark gray through various hues of red, purple, green, and brown. The most common color for the fine-grained tuffs is light green to gray; for the

coarser tuffs, purple to dark gray. In some areas the bedding is very marked; in other areas it may be completely lacking. Most of the beds have gentle dips, averaging about 15°, but greater dips occur adjacent to faults or igneous intrusions. These dips seem to be due to tilting rather than folding. In many places, the volcanic sediments are cut by andesitic dikes. Welded tuffs or lava flows were not seen on the island.

The exposures along the coast are good and here the fine-grained tuffs are best observed. Inland the outcrops are less numerous because the tuffs are generally soft and easily weathered. Outcrops are generally limited to the more massive, coarse-grained breccias and agglomerates It was not possible to trace these beds because they lack marker beds and are not sufficiently well-exposed to be "walked out".

FINE-GRAINED TUFFS: Contrary to the impression gained in the interior land areas, along the coast it may be seen that 70 per cent of the volcanic sediments are fine-grained tuffs which contain only occasional tuff and porphyry boulders. The oldest tuffs occur in the region between Baie de Lorient and the east end of the island. These are dominantly light-colored, well-bedded, and fine-grained. Figure 1 of Plate 2 shows these beds and the nature of the sea exposures at Anse Mongeant.

Evidence that the tuffs were deposited in part above sea level is shown by local channeling and by the occurrence of pisoliths, believed to be formed on land by a combination of driving rain and fresh ash accumulation. On the other hand, limestone nodules, calcareous tuffs, and limestones indicate marine deposition. It is believed that the land area must have been close to sea level with alternating uplift and submergence.

COARSE-GRAINED TUFF-BRECCIAS AND AGGLOMERATES: Interbedded throughout the tuff series are local layers composed of subangular boulders of igneous ejectamenta. The change from a fine-grained tuff to a coarse tuff-breccia may be very abrupt. In addition to the local accumulations of coarse material, fine-grained bedded tuffs are completely absent and the sequence consists of only massive tuff breccias and agglomerates. One of these areas is found in the vicinity of Anse Pascal and extends southeast almost to the outcropping area of the Flamand limestone. Along this coast, the boulders which are up to 5 feet in diameter averaging about 6 inches and resting in a coarse tuff matrix, are composed of tuff fragments and red, black, green, and purplish porphyritic andesites, which are so common throughout the St. Bartholomew Formation. The porphyries contain small feldspar laths but the major portion of the rock is fine-grained matrix of a uniform texture and dark color. No boulders of pumice, basalt, or diorite were found.

Coarse material forms massive outcrops at several places along the path between Lorient and Cul Sac. Other occurrences are smaller in size and too frequent to be located in detail here. Several of the coarse breccias are believed to be "intrusive agglomerates" and will be discussed more fully under the section on igneous rocks.

ALTERATION AND MINERALIZATION: Because of the tropical climate, most of the rocks are highly weathered. Two types of primary alteration associated with the igneous activity have been noted. In the region of the Saline salt ponds, the tuffs are highly silicified and in the region of Anse Reine they are epidotized and chloritized. In both areas, sulfide mineralization has occurred to a limited degree.

In the Anse Reine area, the altered rock is a uniform green color and lacks definite igneous or sedimentary structures. Vague fragmental outlines, also evident in thin section, can be seen only on a few exposures. Normal to the sea cliff, a 400–500 foot adit follows an iron-stained fissure along which the rock contains a small

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PLATE 2. TUFFS AND AGGLOMERATE ON SAINT BARTHOLOMEW

FIGURE 1. ST. BARTHOLOMEW FORMATION AT ANSE MONGEANT

Looking west toward Pointe de Lorient. A 364 foot section of tuffs including the Mongeant limestone was measured here.

FIGURE 2. AGGLOMERATE AT BAIE DE LORIENT

Consisting of large and small pyroclastic boulders. What appears to be talus or soil is the undisturbed matrix of the agglomerate.

FIGURE 1

FIGURE 2

TUFFS AND AGGLOMERATE ON SAINT BARTHOLOMEW

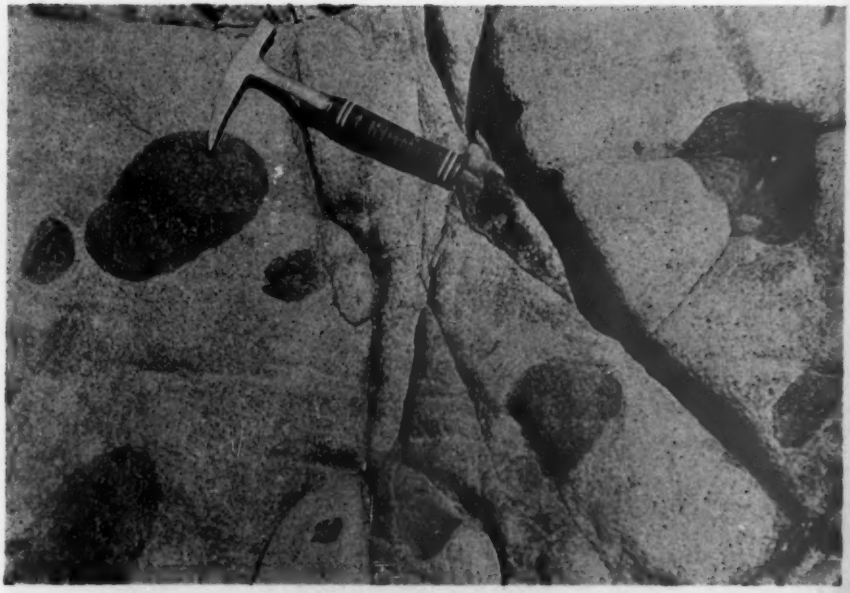

FIGURE 1

FIGURE 2

XENOLITHS IN QUARTZ DIORITE AND MARLS ON SAINT MARTIN

amount of pyrite with a trace of gold[1]. The mineralization and alteration is presumed to be associated with the gasses and aqueous solutions given off by the magmas which produced the near-by andesites.

In the areas surrounding the felsitic intrusions extensive silicification of the tuffs has given the rocks a totally different appearance. This rock, generally gray to cream color but locally stained brown, yellow, or pink, weathers to a hard rough, pitted surface, the silicified portions standing out in relief. In the case of the fine-grained tuffs without initial textural differences, the silicified rock breaks into smooth, almost conchoidal surfaces with sharp, splintery edges. Malachite and limonite stains are found in several localities and at one pit the rock has a small amount of galena and sphalerite. One of the most mineralized specimens contained a trace of gold and a small amount of silver (3.72 ozs. per short ton of 2000 lbs.).

PETROGRAPHY: The tuffs and tuff-breccias are difficult to study petrographically because of their fine-grained texture, the alteration of many minerals to calcite and chlorite, and the saussuritization of the feldspars. The determinations which are possible on the small feldspar laths showed them to be andesine, thus classifying the rocks as "andesitic tuff". Pyroxenes and amphiboles were absent in most tuffs; the common constituents being only plagioclase, magnetite, and glass. Two of the tuffs (243 and 259) contained about 20 per cent of angular quartz suggesting a nearby source.

Figure 3 shows the location of the sites from which various tuff and igneous specimens were obtained for thin section study. Of the 300 rock specimens collected, it was possible to study only a selection of representative types, and only the more significant ones are described in chart form (Table 1).

AGE AND SOURCE: Fossils from the intercalated limestones show the tuffs to be middle Eocene in age. The source of the tuffs is not known, but as they are cut by all the igneous rocks and some agglomerates, they are older than the major volcanic activity on St. Barts. They probably were derived from near-by volcanoes at a distance sufficiently far so that the dominant material deposited was ash, but close enough so that occasional large boulders reached the island by actual "flight" or by water transportation.

[1] Assays by Ledoux and Co.

Intrusive Igneous Rocks and Volcanic Plugs

General statement.—The intrusive rocks comprise about a third of the surface area of St. Barts and probably at depth form the entire foundation of the island. The majority of these are related dark-colored andesites, andesite porphyries, quartz micro-diorite porphyries, and less commonly light-colored quartz diorite porphyry. Most of the rocks belonging to this group appear to be stocklike bodies, although some occur as dikes.

The high peaks in the region between Saline and Grand Fond consist of felsitic intrusions which are so fine-grained and altered that it is not possible to determine accurately their mineral composition. However, in one locality the rock is a dacite in which phenocrysts of plagioclase and quartz are clearly visible on a fresh surface.

In the eastern part of the island, several small bodies of basalt occur. Two of these contain a small amount of olivine, while the others are distinguished by the calcic nature of the plagioclase.

Probable volcanic necks have been identified in several areas where coarse agglomerates are found to crosscut the bedded tuffs. The material of these vents is mainly dark porphyritic andesite.

Gustavia stock.—Cleve (1871) called the "basement rock" of St. Barts a "batholith" of syenite porphyry. Iddings (Vaughan, 1926) identified various specimens from the same mass as either holocrystalline pyroxene andesite or micro-quartz diorite. In this report, the name

PLATE 3. XENOLITHS IN QUARTZ DIORITE AND MARLS ON SAINT MARTIN

FIGURE 1. XENOLITHS OF ANDESITIC ROCK IN THE QUARTZ DIORITE
Parallel lines due to weathering

FIGURE 2. GENTLY DIPPING MARLS OF LOW LANDS FORMATION
Looking northwest along Mullet Pond Bay

"quartz micro-diorite porphyry" has been applied on the basis of the chemical analysis and the thin section study.

This mass outcrops in the vicinity of Gustavia, as well as on the small islands near the harbor (Pl. 1). It is reported to occur on the island of Pain de Sucre which is about 1½ miles west of the harbor. From the distribution of available outcrops a stock-like form is suggested for the intrusion.

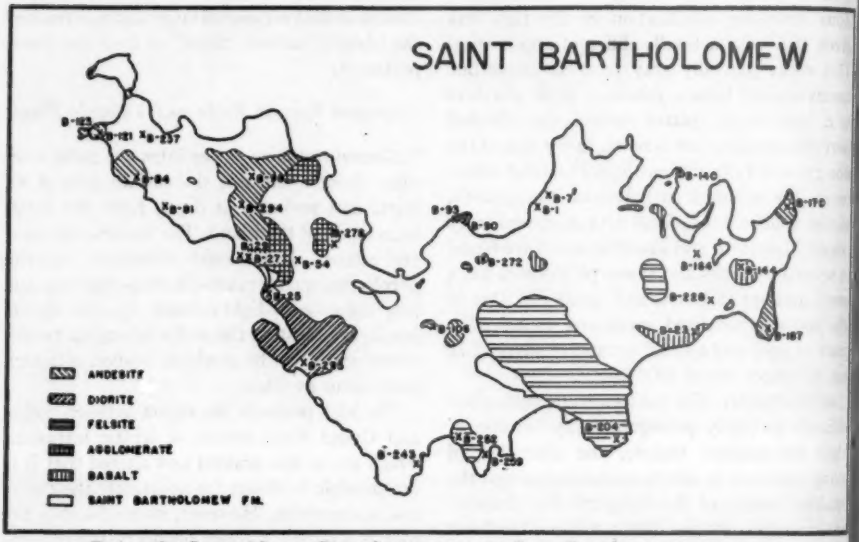

FIGURE 3.—INDEX MAP TO ROCK SPECIMENS FROM SAINT BARTHOLOMEW THAT WERE STUDIED MICROSCOPICALLY

No contacts with the St. Bartholomew formation were seen, although the contact could be located within several feet at the southeast end of Anse du Grand Galet and on the hill overlooking Gustavia to the northeast. Here quartz micro-diorite is found just 6 feet below a continuous outcropping ledge of limestone which forms a cap to the hill. The lack of apophyses of igneous rock or dikes would suggest that the limestone was younger. However, elsewhere on the island andesite dikes cut through the tuff series in many places, so that it seems likely that the quartz diorite here is younger than the limestone though direct evidence is lacking.

The analyzed specimen from the Gustavia stock was collected from a point near the south end of the harbor. These analyses are given on a later page along with the analyzed quartz diorites from St. Martin. At this point it will be sufficient to say that the rock is a typical quartz diorite.

From its megascopic appearance, the rock might be called a "dacite porphyry" because of the apparent fine-grained groundmass. The groundmass, under the microscope, is holocrystalline and therefore the term "quartz micro-diorite porphyry" is preferred. This distinguishes it from the other igneous rocks on St. Barts which have a finer-grained groundmass.

Quartz Micro-diorite Porphyry B-295. This is a specimen of the analyzed material which was collected just southeast of the hospital from the "Gustavia stock" in the town of Gustavia. On the Rock-Color Chart prepared by the National Research Council (1948) the color of the groundmass on a fresh surface lies between greenish-gray (5G6/1) and medium bluish gray (5B5/1). It is fine-grained with scattered large phenocrysts of feldspar which reach a maximum size of 5 mm.

In thin section, the only feldspar is plagioclase. By index oils the composition was determined to lie between $Ab_{60}An_{40}$ and $Ab_{55}An_{45}$ as the maximum

γ and the minimum α were determined as 1.566 and 1.546. The plagioclase phenocrysts are large, rounded and usually twinned. Some are zoned and all are highly altered along the fractures to a dusty material. Some have small patches of chloritic alteration, but no epidote was found.

Augite occurs as small crystals, some twinned, which are colorless to pale green. They are (+) and on the universal stage the 2V = 60°. Chlorite is found replacing some of the augite and occurs throughout the slide as patches. However, it is not possible to determine if it only replaces augite, and some of these areas may represent replaced amphiboles. The chlorite is green and slightly pleochroic and its anomalous color under crossed nicols suggests penninite.

Quartz occurs as small irregular, corroded grains which are interstitial to the other crystals. Occasional crystals of apatite were identified. Magnetite (perhaps in part ilmenite) and pyrite make up about 2% of the rock. The material surrounding the phenocrysts is a holocrystalline mixture of quartz, plagioclase, magnetite and chloritic patches and a dusty alteration product of the feldspars and glass (?).

The Gustavia stock is quite uniform in character. However, in several cases, boulders were found which contain small dikes of coarse-grained, white quartz diorite (B 25). Such rocks were not found in place, but a similar specimen (B 123) was seen cutting andesite porphyry at Anse du Columbier. In both cases, some of the quartz grains are as large as 5 mm in diameter.

Andesite porphyries and andesites.—The most common igneous rock on St. Barts is bluish-gray andesite porphyry, which except for the large percentage of aphanitic groundmass, is similar to the Gustavia stock. In all cases it appears to have an intrusive relationship to the St. Bartholomew formation. On the west side of Anse des Lezards the contact is well-exposed, where slightly updragged tuffs are cut by the andesite.

A summary of the petrographic description is given in Table 1 where it may be seen that the feldspar is andesine or labradorite, commonly highly altered. A small amount of augite or hornblende is commonly present along with pyrite and magnetite (probably titaniferous).

Though andesitic dikes cut the St. Bartholomew formation in many places, little structural control is evident from their strike direction, except that in many cases they strike in a direction towards the nearest intrusive mass. Some of the dikes may occupy faults, as does an 100-foot thick dike on the point to the southeast of Anse du Corossol where a fine-grained tuff is on the north and conglomeratic tuffs on the south side.

Basalts.—Small areas of basaltic rocks were encountered in eastern St. Barts particularly in the area north of Toiny, on the coast of Anse du Fond and south to southeast of Lorient. Olivine-bearing basalts were found as float in the Lorient area and in a dike west of the footpath near Toiny. Several small bodies of basalt south of Anse du Marigot have forms suggesting sills or low-dipping dikes.

The dike west of Toiny contains plagioclase phenocrysts which are notably calcic—An_{93}.

Felsites and dacites.—A large body of felsitic rock outcrops along the coast from Anse de la Saline and Anse du Grand Fond. Exposures are highly weathered. It is a light-colored rock—white, gray, light green to purplish-gray. It is very fine-grained and phenocrysts are sparsely scattered through it. Flowage lines are generally vertical and strike toward the center of the body. On a large cliff along the road running southward from Lorient flow lines are seen to change gradually in attitude from horizontal to vertical. Silicification of the felsite is common.

Volcanic vents.—Volcanic agglomerates are found north of Gustavia, on the point west of Baie de Lorient and on the northwestern tip of the island. Where relations can be observed the agglomerates crosscut the bedded tuffs. Some of the bodies probably represent volcanic conduits.

At the head of a small valley, trending N45W and located west of the Baie de St. Jean and northeast of the home of Monsieur Ledee, an agglomerate is found having an intrusive relationship to the surrounding brown tuff, which is fine-grained and well-bedded with an average strike and dip of N75W 13°SW. Near the agglomerate the dip becomes somewhat erratic; some of the beds having been dragged upward. The contact between the two rocks is irregular, but generally the agglomerate cuts the tuff at right angles. The matrix of the agglomerate near the contact is tuffaceous containing fragments of limestone which in thin section is fossiliferous. One specimen of *Lepidocyclina* was recognized. Farther from the contact, the

TABLE 1.—SUMMARY OF PETROGRAPHIC STUDIES ON VOLCANIC ROCKS FROM SAINT BARTHOLOMEW

Rock	Number	Feldspar	Pyroxenes* and Amphiboles*	Other minerals	Miscellaneous
Quartz diorite porphyry; pale greenish-gray; quartz, feldspar, hornblende < 6 mm.	B 123	Andesine; An_{42} (indices by oil†). Phenocrysts broken and corroded.	Hornblende; twinned, (−), 2V = 80° approximately, $Z'\Lambda c$ = 14°, X = pale yellowish-green, Y = dark brown, Z = dark brownish-green. Partly altered to chlorite.	Quartz; 25% of rock. Epidote; pale yellow pleochroism, (−) 2V = 85°, parallel, extinction.	50% groundmass.
Andesite porphyry; medium dark blue-gray; phenocrysts < 1 mm.	B 121	Labradorite; An_{58} (by Michel-Lévy method). Phenocrysts broken and altered.	Actinolite; slightly pleochroic, parallel extinction, moderate birefringence, (−) large 2V, replaces augite (?).	Quartz; few grains.	65% groundmass.
Andesite porphyry; medium bluish-gray; feldspar < 3 mm.	B 84	Andesine; An_{42} (by Michel-Lévy method). Badly altered to kaolinite, chlorite, and epidote.	Hornblende; pleochroic, twinned $Z'\Lambda c$ = 22°.	Epidote; colorless, (−) 2V = 85–90°. Magnetite-ilmenite, Pyrite.	60% groundmass.
Andesite porphyry; greenish-gray; phenocrysts < 2 mm.	B 98	Andesine; (+) badly altered to kaolinite and some epidote.	Augite; colorless, twinned (+), 2V = 60° approximately. Partly altered to pale-green chlorite (pennine). Hornblende, brownish-green, pleochroic, (−), $Z'\Lambda c$ = 14°.	Quartz; few grains. Magnetite-ilmenite.	60% groundmass.
Andesite porphyry; medium bluish-gray; feldspar < 6 mm.	B 106	Calcic andesine; An_{48} (by Michel-Lévy method). Some broken and altered.	Hornblende; (−) 2V = approximately 80°, X = pale yellowish green, Y = green-brown, Z = dark brownish-green, $Z'\Lambda c$ = 20°.	Magnetite-ilmenite; small crystals.	80% groundmass.
Andesite porphyry; pale bluish-gray; phenocrysts < 5 mm. (Similar to rock B187).	B 170	Calcic andesine; An_{48} (indices by oil†), altered to calcite and chlorite.	Augite; colorless (+). Hornblende; X = pale yellowish-green, Y = greenish-brown, Z = green, $Z'\Lambda c$ = 22°	Chlorite. Magnetite-ilmenite.	50% groundmass; glass and anisotropic flecks.
Andesite porphyry; medium bluish-gray; feldspar < 3	B 294	Andesine; (+) An_{48} (by Michel-Lévy method) al-	Augite; colorless twinned, (+) 2V = 60° (Universal stage)		60% groundmass.

Andesite porphyry; pale bluish-gray; phenocrysts < 5 mm. (Similar to rock B187).	B 170	Calcic andesine; An_{44} (indices by oil†), altered to calcite and chlorite.	Augite; colorless (+). Hornblende; X = pale yellowish-green, Y = greenish-brown,	Chlorite. Magnetite-ilmenite.	50% groundmass, glass and anisotropic flecks.
Andesite porphyry; medium bluish-gray; feldspar < 3 mm.	B 294	Andesine; (+) An_{40} (by Michel-Lévy method) altered to chlorite and epidote.	Augite; colorless twinned, (+) 2V = 60° (Universal stage) altered to calcite and chlorite.		60% groundmass.
Dike-Andesite porphyry; greenish-gray; phenocrysts < 3 mm.	B 93	Sodic labradorite; An_{51} (Michel-Lévy method) altered to kaolinite and chlorite.	Augite; colorless (+), 2V = 60° approximately.	Quartz; less than 10%. Chlorite Magnetite-ilmenite.	75% groundmass. Many small magnetite and plagioclase crystals.
Dike of olivine basalt porphyry; grayish-black; phenocrysts < 4 mm.	B 228	Anorthite; An_{98} (indices by oils†) partly altered to calcite.	None except a few small augites (?) in groundmass.	Olivine, (−) 2V = 85–90°, being altered to pale greenish-yellow serpentine.	40% groundmass. Magnetite, plagioclase, and augite crystals.
Basalt porphyry; black; phenocrysts < 2 mm.	B 23	Bytownite; An_{74} (indices by oils†) altering to calcite and chlorite.	Augite; pale green, non-pleochroic (+), only several crystals.	Pyrite. Magnetite-ilmenite.	50% groundmass. Plagioclase microlites and magnetite dust.
Basalt porphyry; dense, dark gray; few phenocrysts < 4 mm.	B 144	Labradorite; An_{66} (by albite-Carlsbad method) altered to calcite and pennine (chlorite).	Augite; colorless, non-pleochroic, (+), 2V = 65° approximately. Partly altered to calcite.	Magnetite-ilmenite.	50% groundmass. Flow structure.
Olivine basalt porphyry; grayish-black; phenocrysts < 3 mm.	B 272	Bytownite (?); zoned and twinned, partly altered to calcite.	Augite; few large colorless crystals, twinned, zoned, (+) 2V = 52° (Universal stage).	Olivine; (−) 2V = 85–90°, altering to serpentine.	30% groundmass. Augite, plagioclase, and magnetite crystals.
Dacite porphyry; pale red; feldspar < 4 mm, quartz < 3 mm.	B 252	Calcite oligoclase; An_{28} (indices by oil†) twinned and slightly altered.	None.	Quartz; large clear grains, partly corroded. Magnetite-ilmenite.	60% groundmass. Excellent flow structure.
Agglomerate boulder basalt to andesite porphyry; gray.	B 90	Labradorite; An_{60} (by albite-Carlsbad method) large twinned phenocrysts.	Either augite or hornblende are completely altered to pleochroic, green chlorite.	Magnetite-ilmenite.	60% groundmass; brown glass.

* Present only in small amounts, always less than 10%.
† Determined with Na light on minimum alpha and maximum gamma using plagioclase compositions from curve in Kennedy (1947).

matrix is more igneous in character and the fragments or boulders are mostly porphyries, some of which are several feet in diameter. The limestone probably represents xenoliths torn from the conduit walls below as the magna was forcibly injected upwards. The Cayes limestone member should occur only a short distance below the brown tuffs found at the contact on the present erosion surface.

The agglomerate near Public appears to have eliminated the Cayes limestone which can only be traced a short distance south of the main ridge of hills. Likewise the agglomerate near Anse des Lezards is believed to be discordant inasmuch as it appears in a position which should be the extension of the Lezard limestone.

On the west side of Baie de Lorient, the point is composed of an agglomerate which contains, without sorting, both large and small fragments of rock (Pl. 2, fig. 2). The largest boulder is a dark porphyry similar to the one described (B-90), which was 20 by 20 by 50 feet in size. Assuming a specific gravity of 2.8, this rock would weigh 1,750 tons; thus, its source must have been very close to its present position. If not the actual site of a volcanic vent, it must have been close to it. The smaller rocks units are mainly red, green, and gray porphyritic rocks with the matrix itself a mixture of small tuff fragments in a fine-grained igneous (?) groundmass. Associated with this body are several andesitic dikes (B-93).

Structure

The cross sections accompanying the geologic map present a fairly good generalized picture of the structure of the island. The St. Bartholomew formation has gentle dips except in the vicinity of some faults and intrusions. All the observed faults are small, as for example the series of graben and horsts along the coast at Pointe de Lorient. Larger faults may exist, but were not recognized. The correlation of the limestone in the Grand Bois plateau with the Lezard limestone requires postulating a fault with a throw of 300–500 feet extending southward from Baie du St. Jean.

Because the beds dip gently without sharp folding or changes in dip, it seems logical that the structure is due to differential vertical uplift or subsidence accompanying the intrusions of the igneous masses and the volcanic activity. These adjustments associated with the igneous activity resulted in tilting, warping and normal faulting of the sediments. Thus, this relationship is simple in its broader aspects, and the lack of exposures prevents a study of the detailed relationships which are probably much more complex.

Part 2—Geology of Saint Martin

Geography

The island of Saint Martin is located in the west central portion of the Anguilla bank. Its area is about 38 square miles and it has the shape of a triangle with a base of 7 miles and an altitude of 6 miles. Except for the Low Lands, the area surrounding Lac Simson, and Belle Plaine, the island is mountainous. Two ranges or mountainous belts trending NNE-WSW can be distinguished. The larger extends from Koolbaai Berg (730′) and Fort Hill (725′) on the south to the hills in the northern part of the island (East End Point) in the area of French Cul de Sac. This includes Sentry (1129′), Sint Peter (1040′), Flagstaff (1266′), O'Reilly (1280′) and Mt. Paradise (1360′) which has the highest elevation on the island. The eastern and smaller mountainous belt extends from Pointe Blanche on the south to the area south of Anse l'Embouchure. In this range Osstenberg or Naked Boy Hill (985′) is the highest.

Between these two ranges a poorly developed valley called Groote Vlakte or Belle Plaine extends from Groote Baai to Anse de l'Embouchure. This valley is best developed in the northern portion for a series of hills reaching elevations of 590 feet transverse it north of Groote Zoutpan (Great Salt Pond). The area surrounding Lac Simson (or Simson baai Lagoen) is very low and flat with elevations less than 75 feet, except for Mt. Rouge (377′). At the present, the connection of the lagoon with the ocean is at the southeast end of Lac Simson, but prior to the hurricane of 1819, the inlet to this lagoon was near Pointe Bluff.

The island is deeply indented with many bays having beautiful shell-sand beaches. At Grand Case and Groote Baai, sand bars have closed off the bay to form natural lagoons, until recently used extensively to collect the salt from

evaporated sea water. The Low Lands are "tied" to the mainland by sand bars which, in the case of the northern one, is maintained by more resistant rock at Pointe Bluff, Nettle Hill and Colline Hill. Sea cliffs are found between most of the bays with the largest at the northern end of the island and between Pointe Blanche and Anse de l'Embouche.

France owns the northern part of the island with the principal settlements at Marigot and Grand Case, and the Netherlands the southern portion with settlements at Philipsburg and Simson Baai. The inhabitants, as well as visitors, are free to pass across the boundary without restriction. Both countries have "free ports", practically no taxes, and English is generally spoken.

Previous Work

The earliest geologists to study St. Martin were P. T. Cleve in 1871 and Molengraaff in 1885. Spencer (1901) includes a few general notes on the island in his study of the region. The most complete discussion is given by Molengraaff (1931) in which he presents his original data in greater detail. His sketch map gives the general relationships quite clearly, but is lacking in many details and in the exact relationships between some of his units. A good review of the geology of the Dutch part of the island is presented by Westermann (1949).

Preparation of the Map

The field work on St. Martin was done during 2 months of the summer of 1948 and 2 weeks during 1949. The Dutch portion of the geologic map (Pl. 4) was based on a topographic map prepared by the Dutch government in 1911. The French portion of the island has not been surveyed, so that the original field data were plotted on inaccurate maps. Since the completion of the field work, French aerial photographs were obtained and the data transferred to these. The elevations shown on the cross sections are only approximate for the French part of the island.

It was often difficult to decide which name or spelling should be used on the map and in the text because the inhabitants may refer to the same locality by either its Dutch, French or Anglicized name. Unless the locality has an English name, accepted and used by both peoples, the names used in this report are those found on the French and Dutch geographical maps, using each as the authority for its own territory.

Igneous Rocks

Introduction.—More than half the surface area of St. Martin consists of hypabyssal igneous rocks which are intruded into the tuff series and probably underlie the entire island. These rocks, being less resistant to weathering than the silicified and recrystallized tuffs, are found in the valleys and the lower portions of all the mountainous areas.

The igneous intrusives range in composition between granite aplite and quartz basalt, with quartz diorite and andesite porphyry being the most common. Although the field relationships are generally poorly exposed, the rocks are believed to occur as stocks and plugs. Dikes are common, but no lava flows or welded tuffs were identified.

Age relations.—The sequence of igneous rocks may be seen best at Fort Amsterdam. Here the tuff formation is intruded by quartz basalt, which in turn is cut by quartz diorite dikes. One such dike has a fourth-inch chilled margin but otherwise is the same as the quartz diorite of the near-by intrusion. The tuff formation, the quartz basalt, and the quartz diorite, are cut by stringers of aplite. Although the quartz diorite is younger than the andesite, at a few localities, as on the east side of Groote Baai, it is cut by dikes of both fine-grained and coarse-grained, greenish-gray diorite.

Quartz diorite.—The two largest, uniform masses of igneous rock on St. Martin are composed of light-colored quartz diorite. The larger, which occupies about 5 square miles, forms Belle Plaine, the low hills of Middle Region and the Groote Zoutpan depression. The other occurs in the northern part of the island, is somewhat more resistant to erosion, and forms several large hills near French Cul de Sac. Near Grande Case, this quartz diorite has a considerable color variation and parts of it may easily be mistaken for gabbro or anorthosite. A conspicuous feature of both masses is dark inclusions (Pl. 3, fig. 1).

CHEMICAL ANALYSES: Samples from these two quartz diorite masses and the one in St. Barts were analyzed. Figure 4 shows the exact location from which the St. Martin material was collected (near Philipsburg Salt Pond and French Cul de Sac) and the location of the specimens studied in thin section. Table 2 gives the results of the analyses as well as the norms and modes.

All three are similar and are typical of quartz diorite. In the analyses from St. Barts (B 295) and from French Cul de Sac, St. Martin (400), the components differ from one another by less than 0.8 per cent and in many cases by less than 0.3 per cent, suggesting a genetic relationship.

In the C.I.P.W. classification, these rocks fall into the grouping of II (I for specimen 365) 4, 4, 4–5 which in Washington's tables (1917) is characterized by rocks which have been called andesites and diorites. Of the 94 listed i the group, 31 are from the West Indies and 1 are from the Pacific island arcs. An analysi which closely resembles these from St. Marti

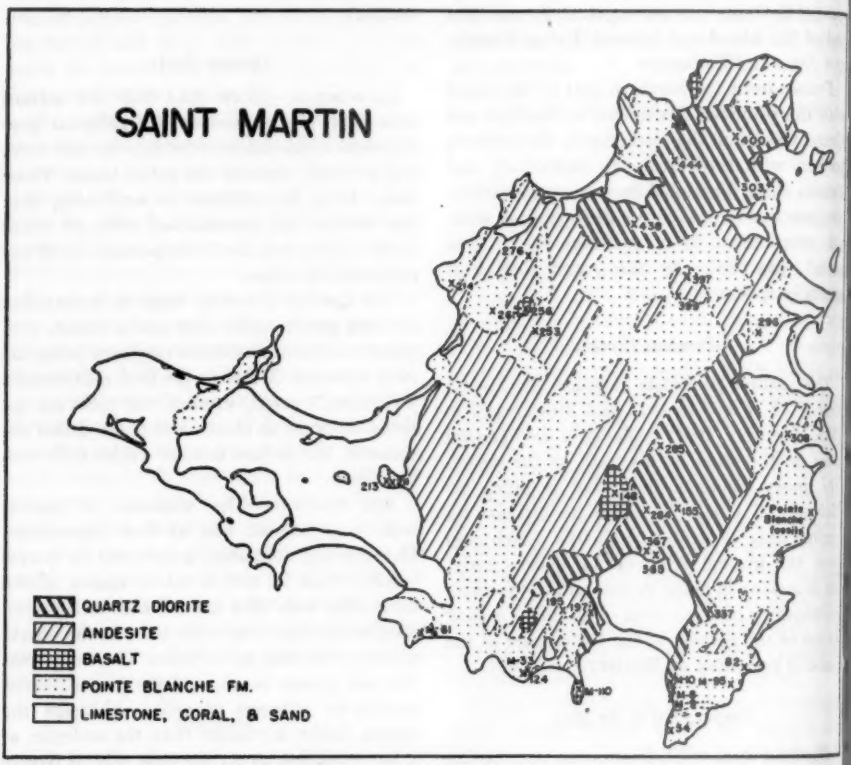

FIGURE 4.—INDEX MAP TO ROCK SPECIMENS FROM SAINT MARTIN THAT WERE STUDIED MICROSCOPICALL

and St. Barts is an andesitic ash collected from the June 1902 eruption of Mount Pelée on Martinique.

PETROGRAPHY: The mineralogy of the two quartz diorite masses is very similar. Plagioclase (sodic labradorite) is the most common mineral and together with quartz comprises about 8 per cent of the rock. The mafic minerals consist of hornblende, partly altered to chlorite, and a small amount of biotite. The dark rock (440) from Grande Case contains a greater amount of biotite and the light-colored rock (438) from Grande Case contains colorless to pale-green augite.

In the vicinity of Middle Region, several

TABLE 2.—DATA ON QUARTZ DIORITES

Analyses by the laboratories at the University of Minnesota

Specimen no. / Analysis no.	Quartz Diorites, St. Martin		Quartz micro-diorite porphyry, St. Barts
	365 R1480*	400 R1481*	B-295 Ri360
SiO_2	66.28	62.83	61.63
Al_2O_3	15.64	16.26	16.86
Fe_2O_3	2.09	2.15	1.99
FeO	2.30	3.22	3.47
MgO	2.12	2.82	2.69
CaO	4.70	5.85	5.41
Na_2O	3.97	3.66	3.79
K_2O	.79	1.22	1.27
H_2O+	1.02	1.14	1.54
H_2O-	.18	.15	.39
TiO_2	.52	.64	.58
P_2O_5	.10	.13	.12
MnO	.05	.10	.13
	99.76	100.17	99.87
Norm.			
Quartz	26.30%	19.82%	17.30%
Orthoclase	4.45	7.23	8.34
Albite	34.06	30.92	31.96
Anorthite	22.24	24.46	25.02
Diopside	.22	3.14	.75
Hypersthene	7.03	8.64	10.59
Magnetite	3.02	3.02	2.78
Ilmenite	.91	1.22	1.06
Apatite	.34	.34	.34
Water	1.20	1.29	1.93
	99.77	100.08	100.07
Mode.			
Quartz	27%	21%	18%
Plagioclase	55	62	67
Chlorite	15	14	12
Augite	—	1	1
Magnetite and pyrite	3	2	2
	100%	100%	100%
Feldspar by norm. (Molecular %)	$Ab_{57}Or_7An_{36}$	$Ab_{51}Or_{11}An_{38}$	$Ab_{51}Or_{12}An_{37}$
	$Ab_{63}An_{37}$	$Ab_{57}An_{43}$	$Ab_{57}An_{43}$
Feldspar by index oils	$Ab_{63}An_{37}$ to $Ab_{50}An_{50}$	$Ab_{57}An_{43}$	$Ab_{55}An_{45}$ to $Ab_{50}An_{50}$
Pyroxene by norm. (Molecular %)	$Wo_2En_{78}Fs_{20}$	$Wo_{13}En_{65}Fs_{22}$	$Wo_2En_{65}Fs_{31}$

*E. Chadbourn, analyst.
†Eileen Oslund, analyst.

small topographic knobs of light-colored quartz diorite porphyry are found. The plagioclase in one of these is more sodic (calcic andesine) and the better developed hornblende crystals sug-

gest that this rock is different from the main mass of quartz diorite. It is likely that it was emplaced slightly later than the quartz diorite.

Quartz diorite 365. This rock is the analyzed material that was collected on the north side of Groote Zoutpan. The rock is light greenish-gray and consists of green chloritic patches surrounded by white feldspar and quartz. It is fairly fine-grained with 50% of the crystals about 2 mm. in diameter. The density at 24°C is 2.72.

The plagioclase which is sodic labradorite is the most abundant mineral. By index oils, the crushed material which would represent the larger phenocrysts was determined to lie between $Ab_{53}An_{47}$ and $Ab_{50}An_{48}$ with minimum γ and maximum α index values of 1.553 and 1.565. Some of the crystals are highly zoned which accounts for their variation in composition. They are all complexly twinned and only slightly altered to a dusty mineral along fractures. No orthoclase was found, although it is possible that a little may exist as small grains along with the quartz in the holocrystalline groundmass.

Hornblende occurs throughout the section as irregular patches with only a few grains having smooth crystal margins. The hornblende is pleochroic with X = colorless to pale brown, Y = medium brown-green, and Z = green. The mineral is negative and 2V = 80°–85° with $Z'\wedge c = 27°$. Most of the hornblende is altered to chlorite and a few grains are replaced by a reddish-brown biotite. It is probable that the hornblende represents the replacement of augite, as is the case in specimen 400. The areas of hornblende are also the sites of concentration for the small magnetite grains and a little pyrite. Magnetite also occurs throughout the section as dust.

The quartz occurs as small anhedral grains which have a corroded appearance. Scattered small crystals of zircon and apatite are found in the section, as well as a few grains of epidote which is colorless to pale greenish-yellow and slightly pleochroic in the colored variety.

Quartz diorite 400. This specimen is the analyzed rock from French Cul de Sac. Its appearance is similar to specimen 365 which is described above, except that it is a trifle darker. Its density at 24°C is 2.73.

In thin section it differs from 365, only in that a few twinned, colorless crystals of augite are present. These were determined on the universal stage to be (+) with 2V = 51½° and $Z'\wedge c = 42°$. The augite is being replaced by hornblende which in turn is being replaced by chlorite and a small amount of biotite. The hornblende is green with X = colorless to pale green, Y = brownish-green and Z = green.

The plagioclase is twinned and the amount of zoning varies in the different sections. By oils it was determined as sodic labradorite of $Ab_{50}An_{50}$ where the minimum α index value was 1.555 and the maximum γ was 1.563. As in section 365, zircon, epidote, apatite needles and crystals, as well as magnetite and pyrite were found sparingly in the section. A few grains of sphene were found.

XENOLITHS: The quartz diorite on St. Martin contains dark inclusions as large as a foot in diameter sparsely scattered throughout the rock (Pl. 3, fig. 1). These are andesitic but lack any evidence of their origin. Most are rounded, a few are angular, and the few which are not equidimensional show no preferred orientation. The quartz diorite xenolith boundary is sharp, although about an eighth of an inch of the quartz diorite is a little lighter colored (the result of the absence of hornblende) adjacent to the xenolith.

Under the microscope, the mineralogy of both rocks seems to be similar. The xenoliths (367) contain a greater abundance of hornblende and have a smaller grain size than the quartz diorite.

Andesites.—The andesites[2] which are very common on St. Martin are all of an intrusive nature, occurring as stocks, plugs, and dikes. No lavas were observed where outcrops are good along the sea cliffs. The exposures away from the coast are poor, and in many cases the extent of the rock unit could only be determined by scattered float; thus, many mapped contacts are approximate in position. It is believed that these rocks were complexly intruded into the tuffs prior to the emplacement of the quartz diorite. They probably represent early magma which came into the area before the country rock was sufficiently heated to allow slow crystallization.

The andesites and andesite porphyries, though mapped as a unit, vary in color from light or dark gray and vary in the size and number of phenocrysts. It is probable that the rocks in this unit range from dacites to basaltic andesites. In the thin sections of andesite, sodic to calcic labradorite is the only abundant phenocryst. Augite, hornblende, or both, to-

[2] To avoid confusion among the European readers, it should be noted that the American usage of the term "andesite" denotes a classification based on texture and composition. Although most andesites are extrusive the term is not limited to extrusive rocks.

gether with magnetite generally comprise less than 30 per cent of the rock. In one section (397), vugs lined with epidote and actinolite probably represent deuteric or hydrothermal alteration. Another section (253) contained a few crystals of hypersthene which is uncommon in these rocks.

Basalt.—Only a few plugs and dikes of basaltic rock occur on St. Martin. These are distinguished by a dark-gray to black color and an aphanitic texture. It is quite possible that portions of the area mapped as andesite may actually belong to this group.

The chemical analysis of the rock occurring at Fort Amsterdam is given in Table 4. The disagreement between the normative and modal feldspar is due to the fact that the plagioclase crystals measured with the index oils are phenocrysts which are more calcic than those in the groundmass.

This rock is somewhat unusual. Because of the high Al_2O_3 and CaO content, it is too basic to be called an andesite. It is a basalt which is rich in calcic plagioclase, and inasmuch as quartz appears in the norm and mode it will be called a "quartz basalt". If 10 per cent anorthite is removed and the analysis recalculated to 100 per cent, a normal basaltic composition is obtained. The C.I.P.W. classification of II 5 5 places the rock in a group which is poorly represented in Washington's tables (1917). Among the 13 rocks listed for this group, three are gabbros, three are olivine basalts, and two are anorthosites.

Quartz basalt M110. This is the analyzed rock from Fort Amsterdam, collected from the sea cliff on the east side of the peninsula. The color would ordinarily be considered dark gray, but by the rock-color chart, it is dusky blue. It is dense and hard with a splintery to slightly conchoidal fracture. It is aphanitic with only a few small phenocrysts.

In thin section, it consists of about 60% groundmass and 40% small phenocrysts of plagioclase and a few augite crystals. The plagioclase crystals are twinned but not zoned. The minimum γ index is 1.570 and the maximum γ 1.582, which according to Kennedy's table (1947) is a calcic bytownite of $Ab_{16}An_{84}$. Extinction on carlsbad-albite twins gave a similar value of $Ab_{12}An_{87}$. The feldspar is slightly glomeroporphyritic.

A few grains of augite occur as euhedral, twinned crystals. They are colorless to pale green, nonpleochroic, and are slightly altered to a dusty appearance. The 2V which was measured on the universal stage is 51° and the indices, determined by index oils, are approximately $\alpha = 1.687$ and $\gamma = 1.713$.

A careful search disclosed several grains of interstitial quartz.

The material in the groundmass has a weathered dusty appearance. It is composed of magnetite dust, small feldspar laths and specks, and probably glass which has been altered. Because of the large amount of groundmass, it was not feasible to make a Rosiwal analysis.

The olivine basalt dike (?) (211) from Mt. Fortune contains olivine crystals which have been almost completely replaced by hematite and serpentine. The orientation of the plagioclase laths indicate that flowage has occurred. The basalt at Williams Hill (148) contains actinolite and serpentine (?) patches which suggest deuteric or hydrothermal alteration.

Aplite dikes and quartz veins.—Aplite dikes are common and are found cutting all the rock types on St. Martin except the Miocene limestones. They are light pinkish-gray, fine-grained, and vary in width from less than half an inch to 5 inches. Under the microscope, they are seen to consist of quartz and orthoclase in about equal proportions.

Many irregularly weathered, brown boulders of quartz as large as 3 feet in diameter are found strewn over the countryside near French Cul de Sac. On a fresh surface, these are moderate orange-pink and contain many small vugs lined with iron-stained quartz crystals. Although not observed in place here, elsewhere small veins of clear, comb quartz may be seen cutting the tuff formation. Quartz in the form of jasper is found in several localities, in two cases associated with manganese mineralization.

Point Blanche Formation

General statement.—The pyroclastic rocks on St. Martin were named by Molengraaff from the type locality of Pointe Blanche where over 350 feet of fine-grained, green and white, banded, and recrystallized tuffs are exposed. Not all the tuffs on St. Martin have been recrystallized, but most of them are fine-grained; the coarse-grained sediments being limited to certain areas. Although the variations may be

TABLE 3.—SUMMARY OF PETROGRAPHIC STUDIES ON VOLCANIC ROCKS FROM SAINT MARTIN

Rock	Number	Feldspar	Pyroxenes* and Amphiboles*	Other minerals	Miscellaneous
Biotite quartz diorite; medium dark gray; average phenocryst = 2 mm.	444	Sodic labradorite as in analyzed rock. Zoned and twinned.	Augite and Hornblende; 18%, mostly altered to pleochroic, yellowish-brown to dark reddish-brown biotite. Biotite (2V = 10° approximately) and chlorite.	Quartz: 15–20%, interstitual, large, anhedral. Zircon. Apatite.	
Quartz diorite; light greenish-gray; average phenocryst = 3 mm.	438	Labradorite; An_{60} (By Michel-Lévy method). Complexly twinned.	Augite; pale green (+), 2V = 50° approximately, twinned, anhedral, making 20% of section. (No alteration to biotite or chlorite).	Quartz; 15%, clear, anhedral. Sphene; few grains.	
Quartz diorite porphyry; light pink; hornblende phenocrysts up to 5 mm.	155	Calcite andesite (?); large twinned and zoned crystals. No Orthoclase.	Hornblende; twinned, large (−) 2V, $Z'\wedge c$ = 18°, X = pale brownish-green, Y = brown-green, Z = green. Actinolite; few pale green fibers, pleochroic, large (−) 2V.	Quartz; groundmass, and large anhedral grains. Sphene, Apatite, Pyrite, and Magnetite.	Pink color probably due to pyrite staining.
Quartz diorite porphyry; light gray; hornblende phenocrysts up to 5 mm.	285	Labradorite; An_{56} (Michel-Lévy method), twinned, and zoned (extinction differing by 9°).	Hornblende; (−), 2V = 75–80° approximately, $Z'\wedge c$ = 17°. X = pale greenish-brown, Y = medium dark brown, Z = green. Mineral probably formerly augite.	Quartz; 15%, but mostly in groundmass.	Fine-grained rock.
Xenolith in quartz diorite; fine-grained; dark greenish-gray	367	Probably labradorite; twinned, zoned, and altered.	Hornblende; (40%), irregular areas, (−) 2V = 80° approximately, $Z'\wedge c$ = 30°. X = colorless, Y = pale green, Z = pale brownish-green. Partly altered to chlorite and biotite.	Quartz; Apatite, Magnetite, and Epidote. Biotite; reddish-brown.	Essentially similar to the quartz diorite.

			Z = pale brownish-green. Partly altered to chlorite and biotite.		
Andesite; dark gray; phenocrysts < 2 mm.	195	Sodic labradorite; An_{54} (Michel-Lévy method), zoned and complexly twinned.	Hornblende; (25%), (−) 2V = 80–85°, Z′Λc = 23°, X = colorless, Y = pale green, Z = green. Some alteration to biotite.	Magnetite-ilmenite; make up 5%. No quartz present.	
Andesite porphyry; medium dark gray; feldspar < 1 mm, hornblende < 10 mm.	253	Calcic labradorite; (−) An_{58} (Michel-Lévy method), twinned and zoned.	Hornblende; (−), 2V = 70, Z′Λc = 18°, pleochroic. Augite; pale green, nonpleochroic, twinned, (+) 2V = 60°. Hypersthene; (−) parallel extinction, pleochroic, few grains.	Magnetite-ilmenite; few large grains.	50% groundmass; magnetite dust and antisotropic.
Andesite porphyry; dark gray; feldspar < 5 mm.	276	Labradorite; (+), An_{54} (by Michel-Lévy method), rounded crystals.	Hornblende; (?), now completely altered to green isotropic chlorite.		50% groundmass.
Dike of andesite porphyry; pale green-gray; phenocrysts < 1 mm.	82	Calcic labradorite; (+), An_{65}, (by Michel-Lévy method).	Augite; (20%), colorless to pale green, (+), 2V = 55° approximately, badly altered.	Magnetite-ilmenite.	60% groundmass.
Andesite porphyry; greenish-gray; feldspar < 5 mm.	307	Labradorite; An_{60} (Michel-Lévy method), twinned, zoned, and altered.	Actinolite; light green, pleochroic, fibrous, (−) 2V = 80°, Z′Λc = 12°.	Quartz; in vugs lined with epidote and actinolite. Epidote and chlorite.	Near contact with Pointe Blanche tuff.
Basalt; dense, medium bluish-gray; no phenocrysts.	256	Small plagioclase crystals; broken and altered to light-green chlorite.	none	Magnetite-ilmenite; appears to make up 50% of the section.	
Basalt; dark gray; aphanitic.	148	Small plagioclase crystals; altered.	Actinolite needles; very small, comprising 30% of the section.	Serpentine patches; pale yellow green, pleochroic, (−). Magnetite and Pyrite.	Evidence of flowage and deutric (?) alteration.

Rock	Number	Feldspar	Pyroxenes* and Amphiboles*	Other minerals	Miscellaneous
Basalt, probably dike; medium dark gray; mostly aphanitic.	211	Calcic labradorite or sodic bytownite; (−) broken and oriented.	Augite (?); colorless, nonpleochroic, twinned, (+) with moderate 2V.	Hematite; probably pseudomorphs after olivine. Serpentine; small amounts.	Flowage structure. Groundmass of plagioclase, hematite and magnetite.

* Present only in small amounts, always less than 10% unless otherwise noted.

quite striking, no satisfactory means of subdividing the formation was found.

The sediments have dips which range from 0° to 45°, averaging about 30°. Folds or large faults were not observed. As most of the beds are dipping to the southeast, the tuffs at East End Point are among the oldest and those at Pointe Blanche are the youngest.

Recrystallized and altered tuffs.—Along the east side of Groote Baai, the relationship between the intrusive quartz diorite and the recrystallized tuffs is clearly observed. In one place, the quartz diorite mass and a diorite dike crosscut the dipping sediments. The dike has a chilled margin of about a third of an inch. In thin section, the quartz diorite (M-10) 1 foot from the contact shows no contact chilling effect and is similar to the rocks in the central portion of the body. At the knife-edge contact, the quartz diorite has an outer one-tenth inch zone of diopsidic augite which is colorless to pale green, nonpleochroic, twinned, $2V = 53°$ (on the universal stage) and $Z'\wedge c = 39°$. At the contact (M-8) on the tuff side is a thin layer of plagioclase, probably andesine, which grades into a fine-grained, altered tuff containing plagioclase, and light green augite. One foot from the contact the recrystallized tuff (M-9) is uniform, dark green, fine-grained, and very hard. It consists of many small light-green diopsidic augite crystals, plagioclase, and a small amount of pale yellow-brown garnet, probably andradite.

The recrystallization extends as much as 1000 feet beyond the mapped igneous contacts. At the Pointe Blanche type locality, for example, the rock (54) contains similar pyroxene crystals, though smaller and less abundant, less garnet, and much more plagioclase. The majority of the tuffs are less recrystallized and show variable degree of crystallization in alternating layers. Evidence of associated igneous activity is shown by aplite stringers, and local andesite float from outcrops which were probably dikes.

At Fort Amsterdam, Fort Hill, and Sentry Hill, similar recrystallization of the tuffs has occurred to form white, green, and dark-green chert-like bands. In one case, a dark-green band was seen to follow a joint, cross cutting the beds, which indicates that solutions or gasses were active so that the recrystallization is at least in part a contact metamorphic effect.

The bedded tuffs of alternating epidote-rich

TABLE 4.—DATA ON QUARTZ BASALT FROM FORT AMSTERDAM, ST. MARTIN

Analysis by the laboratories at the University of Minnesota

		Norm.	
SiO_2	50.30%	Qtz	4.23%
Al_2O_3	20.33	Or	2.22
Fe_2O_3	2.56	Ab	16.77
FeO	6.38	An	45.31
MgO	5.19	Di	7.66
CaO	11.30	Hy	17.29
Na_2O	2.00	Mt	3.71
K_2O	.26	Ilm	1.67
H_2O+	.24	Py	.60
H_2O-	.11	Ap	.34
TiO_2	.90	H_2O	.35
P_2O_5	.13		
Su	.16		100.15
MnO	.17	Norm feldspar (mol. %)	
		$Ab_{77}Or_3An_{70}$	
	100.03	$Ab_{23}An_{73}$	
(Less O for S)	.08	Mode feldspar (oils)	
		$Ab_{14}An_{86}$	
	99.95%	Norm pyroxene (mol. %)	
Eileen K. Oslund, analyst		$Wo_{18}En_{38}Fs_{27}$	

layers (light green) and dense, hard, white and dark-green layers are well exposed at Little Bay. In thin section this rock (124) shows incipient recrystallization having a general "muddy" appearance. The white bands appear to be composed principally of feldspar and the green bands of amphibole, with a large (−) 2V.

An interesting rock (303) forming a small hill south of Baie de Cul de Sac has the external appearance of a banded andesite. However, in this section it is a highly silicified, recrystallized tuff. Most of the rock is composed of quartz and some plagioclase which forms light-gray bands. Darker greenish-gray bands are composed of diopsidic augite and a small amount of irregularly shaped sphene grains. The augite is light green, slightly pleochroic, (+), and the 2V = 60° (approx.).

Epidotization, present only to a limited extent on St. Barts, is common in the tuffs on St. Martin. The epidote is bright yellowish-green, slightly pleochroic (−), 2V = 80–85°, and is prevalent especially in the exposures along the coast. For example, most of the tuffs and tuff-breccias between Geneve bay and Red Pond bay are epidotized.

Of more limited occurrence has been the alteration of fine-grained tuff to a dark-gray, aphanitic hornfelsic rock east of Groote Zoutpan in the vicinity of the manganese mineralization. This mineralization is discussed later.

Unaltered tuffs.—Some relatively unaltered tuffs are present in the Pointe Blanche formation. These include vitric tuffs (214), crystal tuffs (M-61), and lithic tuffs (308). Because of their weathered condition and their fine grained character, little data can be obtained by thin section study. Calcic andesine is the common plagioclase and quartz occurs in several specimens.

Good exposures of unaltered tuff lying unconformably beneath the Low Lands limestones are found along the coast at Kool baai. Here the sequence is mainly composed of thin bedded shaly tuffs, ash, and clay. Interbedded with these are more resistant cherty or calcareous tuffs which form small ledges. One of these, which forms a hard, gray, 1-foot bed, is a quartz crystal tuff composed principally of quartz, and labradorite cemented by carbonate.

Some of the shaly beds are extremely well-bedded; eleven bands of alternating dark and light-colored tuff were measured in half an inch of one specimen. This fine, persistent bedding and the calcareous nature of some of the rocks suggests that the beds were deposited in quiet and probably deep water. In the recrystallization and alteration, these shaly beds apparently became the mafic green layers, while the massive limy and cherty beds became the thicker white layers.

Calcareous and cherty tuffs are found at several localities. At Devils Cupper, nearly 50 per cent of the section is calcareous, apparently recrystallized inasmuch as no Foraminifera are present. Associated with the carbonate are several ledges of cherty beds (M-95). The same association is found at East End Point, except that here vague outlines of corals may be seen in places.

North of Marigot along the main road, the first large hill is capped with what is locally called the "cement stone", a dense, hard, cream-colored chert with a splintery fracture. In thin section, it is very fine-grained chert with a shard-like texture. These shards probably represent organic structures whose form has been destroyed in silicification. It is impossible to determine positively whether they are radiolarian spines.

The coarse pyroclastics, although as abundant on St. Martin as on St. Barts, are found in localized areas rather than throughout the series. The fine-grained tuffs on St. Martin contain no large fragments or boulders of volcanic porphyries as on St. Barts. Instead the breccia-tuffs or agglomerates are found concentrated in certain beds or areas.

Along the coast between Geneve bay and Oyster Pond, the series consist of coarse material interbedded with some fine-grained tuffs. Bedding is not observed in the coarse material, but the fine-grained tuffs indicate a uniform dip and strike of the entire series. The massive beds consist of volcanic boulders of various colored porphyries which range up to 4 feet in diameter. Several small diorite pebbles are found in the series. In the vicinity of Oyster Pond where these rocks are particularly abundant, they have an agglomeratic appearance as the fragments appear partially fused. The matrix has an igneous appearance and the rock

breaks across the fragments rather than around them. West of the pond it was difficult to determine whether some of the rock is an igneous intrusion or an agglomerate.

Other coarse-grained rocks are found at Kool baai, Kay bay, on the hills east of Marigot and Fort St. Louis, and near Anse Guichard. In the interior of the island, the areas of coarse material are less evident because of poor exposures.

A series of coarse volcanic conglomerates outcrop for about 500 feet along the coast a quarter mile west of Etang Rouge. They lie unconformably beneath the Low Land limestone and consist of beds of sorted pebbles and large boulders of light-colored felsites along with fine shaly sediments. Although these beds are less consolidated and less altered than the Pointe Blanche volcanics, they are included in this formation because the limestones lie unconformably on both of them. It is believed that they represent a late stage of the volcanic activity.

Areas of possible volcanic activity.—The coarse volcanics on St. Martin are not sufficiently well exposed to determine whether any of them cross cut the fine-grained, bedded tuffs. The writer is only able to cite certain complex areas of variable rock types which may represent the beveled roots of the former volcanoes on St. Martin.

The most complex area now exposed is along the east coast between Back Bay and Guana Bay Point. Here, many of the rocks are the "agglomerate-igneous" type in which the rock appear to be igneous, but the fragments seem too numerous and distinct to be xenoliths. The area is cut by many diorite dikes and small intrusions, which are difficult to map and interpret because the exposures are limited to the immediate sea coast.

Other areas of coarse volcanic material which may represent sites of volcanic activity are found at Naked Boy Hill, west of Oyster Pond, the ridge between Sentry and St. Peters Hill, and at Mt. Fortune. The latter is a sharp hill whose form suggests a small volcanic neck. It is composed of agglomerate and rises 293 feet from an area of andesitic rock, basalt dikes, and fine-grained tuff.

It is logical to assume that the quartz diorite and other intrusions have been emplaced into the areas of greatest weakness, such as volcanic centers. Thus, the major areas of volcanic activity are probably not exposed, but were located at and above the present sites of the various intrusions.

Age of the Pointe Blanche formation.—The Pointe Blanche formation is unquestionably early Tertiary; either Eocene or Oligocene in age, as shown by fossils discovered near Red Pond Bay. Previously, this formation was considered to be late Cretaceous by Molengraaff (1931) on the basis of correlation with the "Blue Beach" metamorphosed volcanic rocks on Saint Thomas.

John W. Wells has identified two polished coral specimens as *Diploastrea crassolamellata magnifica* (Duncan) 1863 and suggested that they were Middle Oligocene at the oldest. According to Vaughan (1919, p. 476), it is "one of the most important coral species of the American Oligocene, for it seems to occupy almost the identical horizon everywhere it has as yet been found. Its stratigraphic position, as at present known, is middle Oligocene; but the possibility of some specimens being upper Eocene needs to be borne in mind."

W. Storrs Cole has identified the following Foraminifera from thin sections:

Camerina striatoreticulata L. Rutten
Lepidocyclina (*Polylepidina*) *antillea* Cushman.
Operculinoides sp.
Discocyclinids sp.

The *Camerina* were studied in oriented sections and according to Cole the identification of this species is certain and a late Eocene age is indicated. In discussing this foraminiferal fauna, Dr. Cole said that "there are no Oligocene elements in this fauna", but he concludes that in view of the coral evidence, it is possible that the Foraminifera were reworked during Oligocene time.

The beds which contain this fauna are epidotized, calcareous, bedded tuffs and tuff breccias which lack bedding. The fossils are not found at any particular zone. The corals are found as nodular masses of limestone, most of which is recrystallized, and the Foraminifera are scattered throughout the massive beds. The rocks offer no evidence of having been re-

worked. The presence of lithic tuff fragments which would be easily destroyed and the random occurrence of unbroken *Camerina* specimens tend to indicate that reworking has not occurred. Although the form *Lepidocyclina*, which is disk-shaped with thin margins, might seem too delicate to withstand transportation, Cole (1945, p. 81) has reported a case where similar Foraminifera have been reworked.

The beds are conformable with the overlying and underlying beds of typical Pointe Blanche lithology. It seems probable that the entire sequence of sediments is of approximately the same age.

The time factor also must be considered. Following the deposition of the tuffaceous beds now exposed on St. Martin, sediments with a minimum thickness of 2000 feet must have been deposited on the island. Such a thickness was necessary as a cover to insulate the intruded quartz diorite magma so that it crystallized slowly into a relatively coarse-grained rock. Following the intrusion and the solidification of the basalt, andesite, and quartz diorite, a period of erosion must have removed the cover so that the Low Lands non-tuffaceous limestone could be deposited unconformably on a surface which cuts the intrusions and the tuffs. In considering the time required for erosion, it must be remembered that these sediments were not necessarily soft unconsolidated tuffs, as they probably had been subjected to the same metamorphism which made the present Pointe Blanche rock the most resistant on the island.

Considering that the Low Lands formation is lowermost Miocene in age, the sequence of events would seem to require a longer period of time than from Middle Oligocene to the beginning of the Miocene.

The choice is presented of either (1) accepting the Middle Oligocene age of the coral and the rapid succession of the events outlined above, or (2) assuming that the vertical range of the coral does extend into the Eocene to agree with the age determinations of the Foraminifera. This latter choice permits a longer period of volcanic activity and it more closely resembles the geologic history of near-by St. Barts. The author favors the second choice and is calling the Pointe Blanche formation Late Eocene (?) in age, as indicated by the Foraminifera.

Mineralization.—Concentrations of manganese and jasper occur in small areas on the east side of Kay Bay and at the base of the hills on the east side of Groote Zoutpan. The only area where the manganese and jasper are well exposed is along the coast at Kay Bay. Elsewhere, the general extent of the mineralization can be estimated only from a few exploration pits, now overgrown.

The tuff series at Little Bay is the same white and green recrystallized tuff as at Pointe Blanche. In the vicinity of the mineralized area at Kay Bay, the tuffs have been replaced by hematite. In places the sediments are completely replaced to form a red jasper rock which in appearance is very similar to the Lake Superior iron ores of the Huronian type. The manganese, occurring as impure psilomelane with specularite, is found replacing the jasper and epidote beds along fractures and bedding planes. The largest amount of manganese exposed is a vein a foot thick and 18 feet long, pinching out at both ends; thus, present indications are that the quantity is too small to be commercial.

Low Lands Formation

General statements.—Molengraaff divided the younger limestones into two units which he named the Simson Bay limestone and the Low Lands formation. This separation was based on a difference of dip as the Low Lands formation was supposedly horizontal while the Simson Bay Limestone had dips of 15°. Little fossil evidence was presented to support this division.

The present study has shown that dips greater than 15° are found in the Low Lands formation and that the Foraminifera from the two units indicate that the limestones are essentially the same age. In this report, the name "Simson Bay Limestone" has been abandoned and the Low Lands formation is extended to include the limestones between Kool and Simson baai.

Description.—At Kool Baai, the limestone is found resting unconformably on the Pointe Blanche. Near the contact is a lense of marly limestone from which samples were collected for a foraminiferal study. These together with samples from the Low Lands, Tintamarre and

Anguilla were studied by C. W. Drooger (1951). The limestone is generally massively bedded, hard, light gray, and weathers to a gray pitted surface. These beds may be traced to the summit of the 420 foot hill east of Lay bay. Several caves at the base of one of the massive beds near the summit presumably yielded bones of large rodents of the genus *Amblyrhiza* (Cope, 1883).

Most of the Low Lands area is composed of nearly horizontal limestone and marls. Where exposed away from the coast, the limestone is the hard, white variety that weathers to a rough pitted surface. Along the coast some marls are exposed. At Mullet Pond Bay the sequence is composed of soft marls which are light pink, yellow and white and contain iron nodules. These beds may dip as much as 15° (Pl. 3, fig. 2). Many contain poorly preserved micro- and macrofossil remains, and in one area a few coral heads up to 12 by 9 inches were found. Some of these corals were identified by J. W. Wells as:

Siderastrea siderea (Ellis & Solander)
Porites astreoides Lamarck
Favia fragum (Esper)
Montastrea annularis (Ellis & Solander)
sp. cf. M. limbata (Duncan)
Mussa angulose (Pallas) (?)
Meandrina meandrites (Linn.)

He believed these to represent a Miocene or younger age.

A few other fossils were collected from these limestone beds. West of Anse de l'Etang rouge several specimens of *Echinolampas lycopersicus* Guppy were identified by C. Wythe Cooke as being similar to forms found on nearby Anguilla.

Several small collections of macrofossils were made from the Low Lands formation. Because the fossils were poorly preserved, being mostly internal molds, Dr. Richards was only able to give approximate generic determinations.

Age.—Because of the poor preservation and the incompleteness of the collections of the macrofossils, the Foraminifera proved to be the best means for determining the age of the Low Lands formation. As a result of his study, Drooger (1951) says that in all likelihood the limestone from Kool baai (formerly Simson Bay Limestone) and those from the Low Lands (Mullet Pond Bay) as well as those from the Anguilla formation, Anguilla, are all about the same age, namely Early Miocene. He says that the similarity of the Simson Bay and Low Lands faunas strongly favor the opinion that we are dealing with components of one and the same formation deposited under tropical, shallow water conditions.

Structure

No folds or large faults were observed on St. Martin. The dominant dip of the Pointe Blanche formation is to the southeast, except in the vicinity of Sentry Hill and Koolbaai Berg. It is presumably due to tilting associated with uplift and subsidence resulting from volcanic activity and the emplacement of the intrusions. Small normal faults were observed on the west side of Little Bay, and a larger fault is postulated to lie hidden in the valley extending from Pointe Blanche Bay to Groote Baai. In the vicinity of this fault the dip of the Pointe Blanche formation abruptly changes from 0° to 24°. Also, at Pointe Blanche Bay, recent (?) coral deposits which elsewhere are horizontal and found slightly above sea level, are found to be dipping 30°SW. Thus, it is believed that this fault movement is relatively recent.

PART 3—GEOLOGY OF ANGUILLA AND TINTAMARRE

Anguilla

Introduction.—The geology of Anguilla has been described by Spencer (1901), Earle (1923), and Vaughan (1926). Five days were spent on the island in order to round out the study of the Anguilla bank as a complete unit.

Anguilla is a low-lying island about 4 miles northwest of St. Martin. It is 16 miles long, has a maximum width of about 3 miles, and its highest elevation is 213 feet. It is a British island with a negro population. Economic conditions are poor.

"Basement rocks".—Older volcanic rocks called "basement" in the literature, lie unconformably beneath the Anguilla limestone at Crocus Bay and Old Road Bay. Other than a 10-foot bed of tuffaceous material included in the Anguilla formation near Bons Bay, a com-

plete traverse of the island revealed only outcrops of limestone.

At Crocus Bay, tuffs and tuff-breccias are found along the north shore for about 400 feet near Pelican Point. About 40 feet are exposed above sea level with the actual contact covered by slump material. An unconformable relationship is definitely established; the overlying limestones and marls being nearly horizontal and the thick bedded, andesitic tuffs and tuff breccias at N40E 35SE. Most of these are fine-grained vitric and lithic tuffs containing some coarse-grained fragments of andesite porphyries up to 5 inches in diameter. The general appearance of these tuffs is similar to those on St. Martin, so that it is probable that they are equivalent to the Pointe Blanche formation.

On the north side of Old Road Bay, a mass of dark red to black igneous rock, exposed over a 25 by 200 foot area, is found at sea level lying beneath the Anguilla limestone. The rock is highly altered and partially replaced by calcite. In thin section, it is a weathered basalt which contains altered labradorite, a few hypersthene and augite crystals, chlorite, calcite and magnetite.

Anguilla formation.—The entire island is composed of limestone and marls except for the localities already mentioned. The north shore line with its sea cliffs, some almost 100 feet high, follows the general northeast strike of the beds which dip gently southward. The area along the south coast is low; sea cliffs are generally absent, and several large natural salt ponds are located here.

Vaughan (1926, p. 352) described the generalized section at Crocus Bay as consisting of 200 feet of "more or less argillaceous limestone with some beds of harder purer limestone; contains fossil corals . . . as much as two feet in diameter" overlain by "60 feet of hard cavernous limestone". The exposures of marls are mainly limited to the Crocus Bay and Old Road region. The hard cavernous limestone which contains ferriferous nodules, forms small sea cliffs, and weathers to a very rough, karst-like surface, is found throughout the island and is by far the most widespread.

The dips of the Anguilla formation are not uniform, but no folding is observed. The variations of dip may be due to slumping of reef material or to minor fault movements. North of Crocus Bay at Little Bay the beds dip at 75°, 25°, and 0°. Elsewhere several normal faults with displacements up to 30 feet were observed on vertical sea cliffs.

The marls at Old Road and Crocus Bay seem the most fossiliferous and have been studied by various paleontologists. Except for a few localities on the south coast and at Bons Bay, the other limestones seem to lack fossils. Several echinids were collected and these were identified by C. Wythe Cooke as being:

Clypeaster concavus Cotteau (Crocus and Bons Bay)

Echinolampas lycopersicus Guppy (Crocus Bay)

Echinolampas semiorbis Guppy (Crocus Bay)

The age of the Anguilla formation is early Miocene. Woodring (1928, p. 385) says: "The Anguilla formation . . . was for many years called upper Oligocene but is now considered Lower Miocene and has been taken by Vaughan as the type of the lowermost Miocene zone in the West Indian region. . . ." Drooger's study of the Foraminifera substantiates this age assignment. Pliocene limestone has been postulated to overlie the Anguilla formation, but its presence has not been proven.

Vaughan and Spencer both postulated that the Anguilla formation is "part of the coastal plain extending from the mountains of Saint Martin". Now that it has been established that the Low Lands formation on the west side of St. Martin and the Anguilla formation are the same age, this theory seems proven.

Recent history.—E. D. Cope (1883) described bones from three species of a large extinct rodent, *Amblyrhiza*, which were obtained from phosphate earth dug from limestone caves on Anguilla. Associated with the bones was a stone age implement, but it is uncertain whether man was contemporary with the animal.

Cope believed that inasmuch as the "island of Anguilla could not readily have supported a fauna of which these rodents form a part", this is clear evidence that the islands of this bank were interconnected. He concluded that the "submergence of the ranges connecting many of the islands of the Antilles has taken place subsequent to Pliocene times".

Prickly Pear Cayes.—Northwest of Anguilla a series of low islands extend from Old Road Bay to Dog Island. Two of these, the Prickly Pear Cayes, were visited to obtain samples of the tuffaceous material that supposedly occurred here. The islands are composed of cross-bedded foraminiferal limestone. No age can be assigned to these beds except that they are contemporaneous or younger than the Miocene marls on Anguilla.

Tintamarre

Tintamarre is a small island about a half square mile in area 2 miles northeast of St. Martin. It is composed entirely of limestone which strikes northeast and dips gently to the southeast. Cliffs of these limestones are found along the northwest shore of the island.

Most of the limestone is hard, light-cream to white in color, and weathers to a pitted surface. It is very similar to the limestones of the Anguilla and Low Lands formations. Portions of the limestone appear brecciated and probably represent reef accumulations. Between North Cove and Mice Hole, a series of calcareous and tuffaceous shales are found. These contain small pecten fragments and a considerable quantity of selenite.

On the basis of certain *Lepidocyclina* Foraminifera, Drooger (1951) believes these limestones to be Late Oligocene in age, thus slightly older than the limestones on St. Martin and Anguilla. However, because of the similarity of rock, the Low Lands formation is extended to include these beds on Tintamarre. Thus, the limestones on Tintamarre are believed to represent the oldest portion of the formation. Several echinoids common at North Cove were identified by C. Wythe Cooke as *Clypeaster concavus* Cotteau.

Conclusions

Regional Setting

Lesser Antilles.—The Lesser Antilles have been divided into two groups of islands, the inner (western) group of recent volcanism, and an outer (eastern) group called the "limestone Caribbees". Anguilla, St. Martin, and St. Bartholomew belong to this latter group as do the islands of Sombrero, Barbuda, Antigua, Grand Terre of Guadeloupe, Desirade, and Marie Galente.

Sombrero, the northernmost of this group, is a small, low, flat island composed of limestone which is lower Miocene if Hubbard's (1923, p. 72) correlation with the Quebradillas limestone on Puerto Rico is correct. Schuchert (1935, p. 755) refers the Sombrero deposits to the Anguillian (lower Miocene) to correspond to the limestone on Anguilla, the nearest island to the southwest. Only flat-lying Quaternary limestone is exposed on the low island of Barbuda.

The geological history of Antigua is similar to that of St. Barts and St. Martin. The writer studied the mountainous portion of Antigua and is preparing a report on this study. The oldest rocks on this island are a series of tuffs and tuff-breccias which are conformably overlain by the Antigua limestone (Upper Oligocene). Both the limestones and tuffs appear to be about the same age. The mountainous area consists of volcanic breccias, agglomerates, and igneous intrusions, some of which probably represent volcanic conduits. The igneous rocks, predominantly andesitic, range from olivine basalt to dacite and are all relatively fine-grained.

To the south, pre-Miocene volcanic rocks are found on Desirade and Grande Terre. Barrabe (1934) reports andesites and rhyolite flows and intrusive granodiorite overlain by Miocene limestone on Desirade and granodiorite overlain unconformably by Miocene limestone and tuff on Grande Terre. Marie Galante, an island southeast of Guadeloupe, is the southernmost island of the outer group and is capped with recent limestone (Woodring, 1928).

The inner group consists of the islands of Saba, Statia, St. Kitts, Nevis, Montserrat, Guadeloupe, Dominica, Martinique, St. Lucia, St. Vincent, the Grenadines, and Grenada. In historical records dating from 1692, volcanic activity has been reported on each of these islands except Saba and Grenada. Tuffs as old as Oligocene are found on Martinique (Senn, 1940) and in Carriacou, one of the Grenadines (Trechmann, 1935), suggesting that volcanic activity in the arc began about this time. The volcanics of these islands are predominantly andesitic.

No true granite has been found on either of the island groups. Hess' granitic pebble from the Cassada Garden gravels on Antigua (Senn, 1940) is similar to the localized lenses of quartz diorite that have differentiated from the quartz micro-diorite porphyry on St. Barts. A small remnant outcrop of quartz diorite is found along the southern shore of Antigua; the quartz-rich diorite pebbles were probably derived from the seaward continuation of this mass.

Other granitic rocks reported in the West Indies have not been found in place, and it is suspected that these represent foreign rocks brought to the island's shores as ballast on the sailing vessels. Along the shores of Groote Baai on Saint Martin, the following foreign rocks were found:

Fine-grained, gray, quartz sericite schist.
Coarse-grained feldspar biotite augen gneiss.
Medium-grained white garnet gneiss
Medium-grained biotite quartz gneiss
Pink hornblende granite
Light colored granite
Pink rhyolite conglomerate
Pyrite sericite schist
Dense black limestone (from St. Barts?)

Many of these are similar to rocks between Baltimore and Maine, and it is probable that they were brought to the island in sailing vessels engaged in the rum and molasses trade.

Greater Antilles and Virgin Islands.—The volcanic sediments and intrusions in the Greater Antilles and Virgin Islands generally are older and have been subjected to stronger deformational forces than those in the Lesser Antilles. In Cuba the oldest dated rocks are Jurassic, while in Hispaniola and Puerto Rico they are Cretaceous. These have been intruded by ultramafics and diorites. The first strong deformation and the intrusion of the ultramafics is probably of late Cretaceous age (Maxwell, 1948). In Cuba a second deformation occurred during late middle Eocene and local folding of Oligocene beds has occurred. These may correlate with Eocene diorite intrusions (Vaughan, 1926) and late Miocene folding in Hispaniola. The coastal plains on the north side of Puerto Rico consist of undisturbed Middle and Upper Oligocene and Lower Miocene limestones (Meyerhoff, 1933).

The oldest rocks on Saint Thomas and Saint Croix, Virgin Islands, are late Cretaceous. On St. Croix, these are a series of sandstones, shales, and limestone with interbedded tuffs. The rocks on St. Thomas are principally andesitic breccia and latite (Vaughan, 1923). Subsequent to the deposition of these beds Vaughan reports that "there was intense deformation, which resulted in tight folding in Saint Croix where dips of 30° or more are common . . . in St. Thomas they are 50° or more". Diorite masses are intruded into these sediments. On a near-by level plain, younger middle Oligocene, late Oligocene, and early Miocene limestones are found. On Saint Croix, these were gently folded and strongly faulted (Cederstrom, 1941).

Barbados, Tobago, Trinidad, and Northern Venezuela.—In Barbados, middle and upper Eocene clastics have been deformed and covered by mud flows, and all in turn have been strongly folded and are overlain by the Oceanic series of upper Eocene and early Oligocene chalk, radiolarian earth, and tuff (Senn, 1940). These beds also are folded slightly and the series is overlain by Upper Oligocene-Miocene marls and Pliocene-Pleistocene coral rock

Metamorphosed rocks of probable Cretaceous age intruded by serpentines are found in Tobago. Metamorphosed Jurassic and Cretaceous rocks are found in the North Range of Trinidad, and the Coast Range of Venezuela probably consists largely of metamorphosed Cretaceous rocks with ultramafic intrusions. The metamorphism and the intrusion of the serpentines is believed to have occurred in late Cretaceous time (Maxwell, 1948).

Regional Tectonics

The negative anomaly strips and the associated island arc structures have led Vening Meinesz (1934) to advance the hypothesis of crustal downbuckling. This hypothesis has been applied to island arcs in general by Umbgrove (1947; 1949) and to the West Indies in particular by Hess (1938) and will not be repeated in this paper.

The islands of the Anguilla bank lie on the geanticline to the west of the negative strip. The geologic history outlined for these islands is in harmony with the general theory and explains some of the later tectonic activities.

Summary

No Cretaceous rocks are exposed on the Anguilla bank. Inasmuch as the strong deformation and intrusion of ultramafic rocks occurred during late Cretaceous time in the Greater Antilles, it is supposed that, in the Lesser Antilles, the record of this event lies beneath the islands or beneath the ocean to the east. The oldest rocks on Saint Bartholomew are tuffs of Middle Eocene age while those on Saint Martin are Late Eocene. Both series contain pyroclastic pebbles and boulders, localized in certain beds on St. Martin but found throughout the series on St. Barts. The fine-grain size and younger age of the St. Martin tuffs are interpreted as meaning that the center of volcanic activity during Middle to Late Eocene was distant from the island. The center may have been in the vicinity of St. Barts, inasmuch as concentrations of coarse volcanic material are found throughout the Saint Bartholomew formation. The sedimentary evidence indicates that, during the Middle Eocene, St. Barts was near sea level, alternately above and below it. The thick, nontuffaceous, fossiliferous limestones represent long periods of quiet marine sedimentation. Thus the island was not the actual volcanic center at this time. It is believed that the volcanoes lay to the east of St. Barts because no thick Middle Eocene tuffs are found on St. Martin.

During Late Eocene time, the thick, dominantly fine-grained Pointe Blanche formation was deposited on St. Martin; thus, the volcanic activity probably shifted to a nearer position, perhaps on St. Barts itself, as is indicated by intrusive agglomerates. The sedimentary cover needed for the crystallization of the quartz diorite on St. Barts may have been deposited at this time. At a later time, post-Late Eocene, the site of volcanic activity had shifted to the island of St. Martin where a similar cover was deposited. Finally, the activity shifted westward beyond St. Martin to Saba by late Tertiary.

These movements of the center of volcanic activity probably represent the eastward movement of the crust towards the downbuckle. If the geanticlinal axis and the axis along which the centers of volcanic activity occurred maintained a given distance from the axis of the downbuckle, as the crust moved eastward into the buckle the two axes would appear to move westward in regard to any given point on the crust. Thus, the westward shift of volcanoes from east of St. Barts to the island of St. Barts, to the island of St. Martin, and finally to Saba, sheds additional light on the continued maintenance and development of the downbuckle during the Tertiary.

The tuff formations on both St. Barts and St. Martin are cut by intrusive agglomerates, dikes, and hypabyssal bodies of basalt, andesite, and quarrtz diorite. These probably represent the roots of the volcanic activity. On St. Martin, the tuffs have undergone contact metamorphism whereas on St. Barts they are less altered except in the vicinity of the felsitic intrusions where they are silicified. Uplift and subsidence associated with the volcanic activity and intrusions of the stocks and plugs resulted in the tilting and faulting of the tuff series, those on St. Barts being more disturbed.

The coarse grain size of the quartz diorite indicates that at least 2000 feet of cover have been eroded from the islands. On St. Martin this erosion was accomplished by the end of the Oligocene. On the west side of the island, the Early Miocene Low Lands formation was deposited on this surface. The lack of tuffaceous material in this formation indicates the absence of volcanic activity at this time. This same formation covers Tintamarre, an island to the northeast, but here it is Late Oligocene in age. The surface may have extended to Anguilla where outcrops of similar tuffs are unconformably overlain by marls and limestone of Early Miocene age. On St. Barts the limited outcrops of younger limestone at Petite Cul de Sac may represent a similar Oligo-Miocene history.

At some later date, the islands were uplifted and the Oligo-Miocene beds were slightly tilted and faulted. Folding and faulting of Miocene beds is also recorded in St. Croix. Sometime during the Pliocene to Pleistocene, the islands of the Anguilla bank were probably higher and connected, as indicated by the occurrence of fossil remains of large rodents. Rutten (1935) and Vaughan (1918) believe that a land connection with South America may have existed at about this time.

The bank is now submerged to about 200 feet below sea level so that the former mountainous areas of the once large island are now exposed as the islands of St. Barts, St. Martin, and Anguilla.

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Short Notes

DEFORMATION OF BORE HOLE IN MALASPINA GLACIER, ALASKA

BY ROBERT P. SHARP

Demorest's (1942, p. 31–38; 1943, p. 365–373) exposition of extrusion flow in glaciers has not enjoyed universal acceptance. Skepticism has been especially strong in England where physicists have produced well-considered arguments and calculations showing that extrusion flow is a mechanical improbability (Orowan, 1949, p. 233–236; Nye, 1951, p. 565; 1952a; 1952b). Their analyses necessarily involve gross simplifications and are based in part upon assumptions concerning the physical properties and behavior of ice under long-continued confining pressure and stress so the validity of their conclusions needs independent confirmation.

For this reason, field tests of the mode of flow in glaciers are in order, and one such test was initiated in June 1948 on the Jungfraufirn at the head of Great Aletsch Glacier in Switzerland (Perutz, 1949). The results of these observations do not support the concept of extrusion flow (Perutz, 1950; Gerrard, Perutz, and Roch, 1952, p. 552–553, 556). However, the test site was at the head of a valley glacier, whereas extrusion flow is presumably best developed in sheets of ice of gentle surface slopes and nearly flat floors. For this reason similar observations in a more suitable situation appeared desirable.

Malaspina Glacier, a large sheet of ice covering more than 1000 square miles on the flat coastal plain of southern Alaska, was selected as the most accessible ice mass possessing conditions best suited to extrusion flow. A test site was selected near the center of this sheet 11 miles from its southern edge and 13 miles from the base of the mountains to the north. A north-south seismic-reflection profile, approximately 10 miles long, shows the ice at the test site to be 1950 feet thick. Here the subglacial floor is nearly 600 feet below sea level, and it slopes gently upward to the south, in opposition to the southward flow of the glacier. Average slope of the ice surface along the profile line is 60.5 feet per mile to the south, but in the vicinity of the test site it is 34.8 feet per mile southward. These conditions should give rise to extrusion flow if such exists.

A bore hole approximately 2 inches in diameter was sunk vertically 1000 feet into the ice by means of an electrically heated hot point. A portable electrical generator producing 2500 watts at 220 volts provided the energy, and the hot point, with a resistance close to 22 ohms, was operated in the neighborhood of 7 amperes by means of a variable resistance in the circuit. Aluminum pipe with an inner diameter of 1.38 inches and outer diameter of 1.66 inches, in 10-foot sections joined by aluminum couplings, was used as the drill stem. Boring ceased at a depth of 1000 feet when the hot point burned out or was shorted. This hole falls 950 feet short of attaining the glacier's floor, but the boring party was delighted to reach 1000 feet in view of the many trials and tribulations besetting the operation. Insofar as known this is the deepest hole yet made in a glacier by mechanical drilling or thermal boring. With proper equipment, a temperate glacier, and lack of excessive shearing or flowage in the ice, it seems that holes several thousand feet deep should be possible by thermal boring. The pipe was left in the hole, and its orientation surveyed by an inclinometer giving reproducible inclination readings accurate to 0°05′ and azimuth determinations accurate to 2° or 3°. Inclinometer records were made at 50-foot intervals.

At the time of the initial survey on 28–30 July, 1951, approximately 2 weeks after boring was completed, the greatest deviation from vertical was 3°00′. The attitude of the pipe in the bore hole at this time is shown by curve A (Fig. 1) as it would appear in a vertical plane bearing S. 25° E., which is the direction of ice flow inferred from foliated structure in the

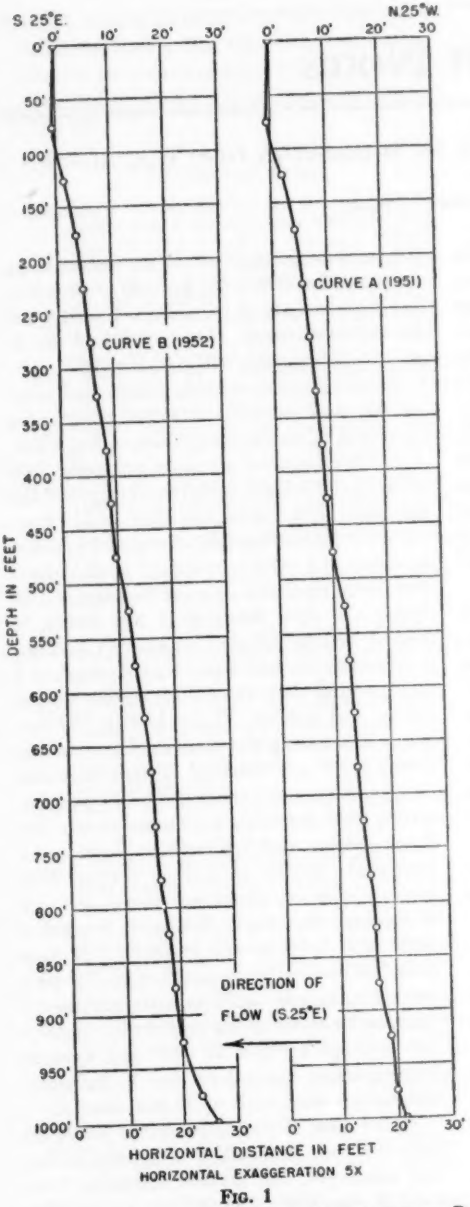

FIG. 1

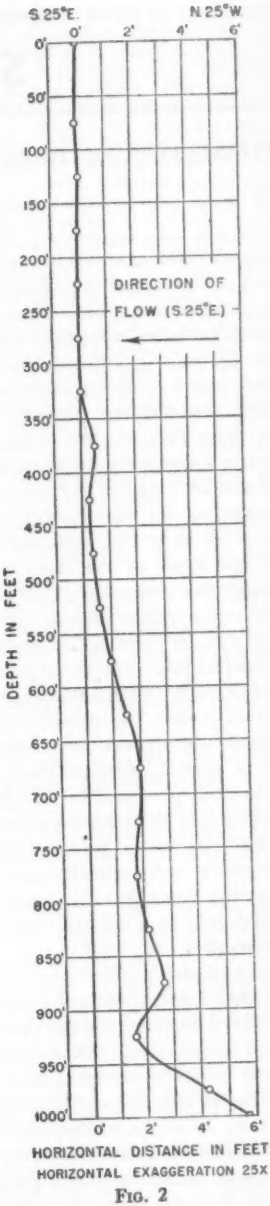

FIG. 2

FIGURE 1.—ORIENTATION OF PIPE IN MALASPINA GLACIER

Curve A represents initial orientation, and Curve B represents orientation after one year as plotted in a vertical plane parallel to direction of flow. Absolute amount of flow not known, so horizontal separation of curves is arbitrary.

FIGURE 2.—DEFORMATION OF PIPE IN MALASPINA GLACIER IN ONE YEAR

Plotted as deviation from a straight vertical line.

glacier. A second inclinometer survey on 23–26 August, 1951, showed that deformation during the intervening 3½ weeks was insignificant. A third survey, on 15–17 August, 1952, recorded perceptible deformation, and the results are plotted as curve B (Fig. 1).

Deformation between late July 1951 and mid-August 1952 was surprisingly small. The pipe shows no change exceeding the observational error to a depth of 300 feet, but below that deformation increases slowly at a relatively uniform rate, with local minor variations and a small acceleration below 900 feet (Fig. 2). The greatest inclination recorded, 3°55′, was at a depth of 950 feet, the change here being from 1°55′ on 30 July, 1951, to 3°55′ on 16 August, 1952.

Total absolute movement is not known, as the test site is too far from fixed triangulation points to permit such a measurement. Differential movement between the top and bottom of the hole was 5.75 feet. This need not necessarily represent the absolute amount of differential flow, because the ice may have moved past the pipe to some degree by pressure melting and refreezing. Amount and distribution of deformation are best shown by a plot in which deviation from the original attitude of the pipe is plotted against a straight vertical line (Fig. 2). This plot shows clearly that during the first year differential flowage occurred only at depths greater than 300 feet.

As yet the deformation recorded is too slight to permit firm conclusions concerning the mode of flowage in Malaspina Glacier, and further inclinometer surveys of the pipe must be made in future years. The initial results are certainly not consistent with the mechanism of extrusion flow as expounded by Demorest. Figure 2 suggests increasing differential flow with depth, but the overlying ice appears to be carried along by this flow in a manner contrary to the concept of extrusion flow.

Observations in this bore hole will be repeated annually until more marked deformation is recorded and as long as the pipe remains open. A detailed account and analysis will be forthcoming as soon as more definite results are obtained.

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